The Royal Aeronautical Society

(FOUNDED 1866)

with which is incorporated The Institution of Aeronautical Engineers

No. 255. MARCH, 1932. Vol. XXXVI.

PROCEEDINGS

THIRD MEETING, FIRST HALF, 67TH SESSION

The Third Meeting of the first half of the 67th Session of the Royal Aeronautical Society was held in the Lecture Theatre of the Royal Society of Arts on Thursday, November 5th, 1931, when a paper, entitled "Safety in Spinning," by Mr. H. E. Irving, B.Sc., A.F.R.Ae.S., and Mr. A. V. Stephens, was read and discussed.

Mr. H. E. Wimperis (Director of Scientific Research at the Air Ministry) presided.

The CHAIRMAN: The subject was one of the most recondite that the aeronautical world had to study, and the authors of the paper came from two of the experimental stations which in this country were concerned with the investigation of spinning. These two stations were the National Physical Laboratory, Teddington, and the Royal Aircraft Establishment, Farnborough. The other two stations concerned with such investigations, on the more practical side, were Martlesham and Felixstowe. Most of the work had been done at the National Physical Laboratory, where Mr. Irving had been working for nearly twenty years; for some years he had been a Senior Scientific Officer, and in 1929 was awarded the Wakefield Gold Medal of the Royal Aeronautical Society. Mr. Stephens had been at Farnborough for a year or so, having gone there from Cambridge, and it would be realised that his work at Farnborough, if brief, had been of an intensive character.

The paper was then read by Mr. Irving, who showed two cinematograph films, demonstrating respectively an American seaplane in a spin from a considerable height to the ground, and the dropping of models in free flight model experiments in the balloon shed at the R.A.E.

Mr. Stephens demonstrated spinning by means of models in a 2ft. diameter vertical wind tunnel erected in the lecture theatre.

SAFETY IN SPINNING

BY

H. B. IRVING, B.Sc., A.F.R.Ae.S., & A. V. STEPHENS

INTRODUCTION

The purpose of this paper is to give some account of the work on spinning and the progress which has been made since S. B. Gates and L. W. Bryant presented their paper to the Society, which was published in more comprehensive form by the Aeronautical Research Committee as R. & M. 1001.

Although it is distinctly possible that the aeroplane of the future will be unspinnable it is a fact that the great majority of present day aeroplanes are capable of taking up the spinning motion either inadvertently or by deliberate intent on the part of the pilot. If it were really true that all those aeroplanes

which apparently require to be forced into a spin would never inadvertently fall into one, a considerable number could be definitely classed as safe by forbidding spinning on such aircraft. As things are at present, however, no reliance can be placed on any assumption that an aeroplane which is usually unwilling to go into a spin will not under some unusual circumstances, such as, for example, flying in clouds, fall into one; and it sometimes happens that it is just those unwilling aeroplanes which give trouble once a spin has been allowed to develop. It seems best, therefore, as is the present practice, to conduct spinning trials on all aircraft in which aerobatics may be performed. In our paper we have accordingly considered the various data which have become available chiefly from the point of view of safe recovery in a spin, but here we have met the greatest difficulty in the interpretation of the data in view of the complication of the motion of recovery, and of the fact that, as will be seen later, the pilot's evidence as to what he and the aeroplane actually do during recovery has sometimes been found to be unreliable. For example, on one occasion a pilot who has had much experience of spinning realised during a protracted recovery that he was applying rudder *for* the spin when he had thought it was against the spin.

Before dealing with the various developments which have taken place we give a short account of the nature of the motion in a spin and the forces and moments set up. We next devote some consideration to the kind of moment —rolling, pitching or yawing—which is likely to be most effective in putting a stop to the spin. This puts us into a better position to review from the point of view of recovery the model work which has been done both in the wind tunnel and by free flight dropping tests, and we point out the distinct and complementary functions of these two types of experiment. The model experiments include the effect of various modifications to the shape and arrangement of the tail plane, fin and rudder, seaplane floats, differential, rigged up and floating ailerons and interceptors, and alterations in the moments of inertia of the aeroplane.

Next we pass to developments in the technique of full-scale experiments and include in this section the question of the determination of the moments of inertia. This is followed by the presentation of spinning diagrams, calculated from model data, for a number of aeroplanes, and these are discussed in the light of such full-scale data as have been obtained on them, with particular reference to recovery. The working out of these diagrams gives an insight as to the manner in which the aerodynamic properties of the wings and yawing moment inertia affect the spin and are inter-related. This brings in the question of the effect of stagger and wing section, which we discuss; finally we sum up by giving a number of conclusions at which we have arrived.

The Spinning Motion

The path described by the centre of gravity of an aeroplane in a spin is a steep spiral whose axis is vertical, the motion along the spiral path being combined with a rotation about the axis of the spiral (see Fig. 1). The axis of the body may be anything from about 20° to the vertical to nearly flat; at the same time the span of the wings is never very far from the horizontal.

The radius of the spiral described by the centre of gravity is generally so small that the motion of the centre of gravity might almost be judged to be vertical; and, this being so, what we think of as the *lift* acts nearly horizontally. Thus, to a fair approximation, the balance of forces in the vertical and radial directions may be expressed by the equations:—

$$\text{Drag} = \text{Weight of aeroplane}$$
$$\text{Lift} = \text{Centrifugal force},$$

and very little thought is required to see that in general the flatter the spin the smaller the radius of the spiral, which would become zero for a truly "flat" spin with the body horizontal.

If now we resolve the simple spiral motion of the spin into its components along *wind axes,* it becomes in general the forward motion along the direction of linear motion in the plane of symmetry combined with the motions we speak of as rolling, yawing, pitching and sideslipping. Of these angular motions the one which always preponderates over the other two is the rolling velocity. The rate of yaw rarely rises to more than one twentieth of the rate of roll while the

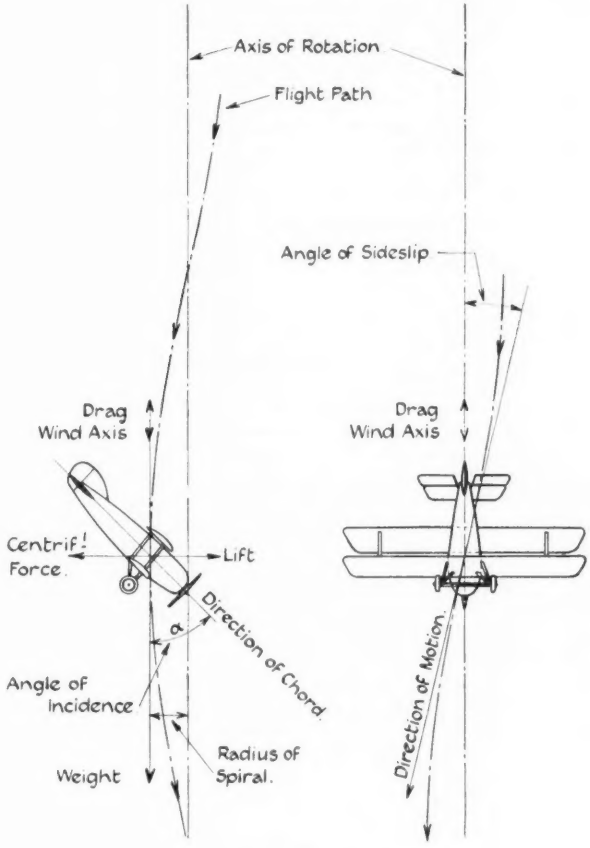


FIG. 1.
Diagram showing motion and forces in a spin when the span is horizontal.

rate of pitch may become perhaps one-third but is usually much less. It is because of these facts that the simple auto-rotation or rolling balance experiment in which the model is rotated about the wind axis through the centre of gravity —or in other words, is given a pure rate of roll—reproduces approximately the motion of the spin. Nevertheless, it is of the greatest importance to realise that in the actual spin the lesser motions of pitching, yawing and sideslipping may all be present and to take them into account in applying the results.

It is interesting to note the connection which exists between the attitude of the spinning aeroplane and its sideslip and rate of pitch. We have stated that in the spin the span is usually not far from the horizontal. At the most it may be inclined about 20° from the horizontal either way. It is easily seen that if the span is actually horizontal, since the path is a spiral there must be sideslip (which we shall call *outward*) of amount corresponding to the angle of the helix; and that, consequently, if the span is tilted inner wing downwards through this angle, the sideslip becomes zero. It is thus clear that whereas if an aeroplane spins with its outer tips down there must be considerable outward sideslip, if it spins with its inner tips down there may be little or no inward sideslip unless the tips are considerably down.

Another point about the motion is that when the span is horizontal (with outward sideslip) there is no pitching motion about the transverse axis because this axis is then at right angles to the axis of the resultant rotation (the vertical); also when the span is inclined inner tips down so that there is no sideslip, there is a positive rate of pitch. This is perhaps not immediately obvious, but it may more easily be envisaged that the velocity component in the plane of symmetry normal to the body is less at the nose than at the tail. So may be seen the nature of the connection between attitude of the aeroplane in the spin with respect to the earth and its most important subsidiary motions of pitching and sideslipping. We may sum this up as follows:—

Span	horizontal	corresponds to	outward sideslip.
,,	,,	,,	zero rate of pitch.
Outer tips down		,,	considerable outward sideslip.
,,	,,	,,	negative rate of pitch.
Inner tips down		,,	little sideslip (outwards or inwards).
,,	,,	,,	positive rate of pitch.

Next as to the nature and magnitude of the couples and forces set up by the main and subsidiary motions:—

We should first make it quite clear, however, that although we consider the motions with reference to wind axes it is generally more convenient to treat of the forces and moments set up by these motions in terms of body axes and this procedure we here adopt; one reason being that the rudder gives a pure yawing moment with reference to body axes, another that in dealing with moments of inertia body axes are approximately *principal* axes.

The rolling motion which is the main angular motion of a spin affects all three forces and moments on the aeroplane, but the effect on the moments is more important than on the forces. So far, drag is the only force on which the effects of rolling have been observed. Lateral force due to rolling should not be of any importance, while the effect of rolling on normal force may be estimated roughly, and generally with sufficient accuracy, from strip theory. The effect of rolling on pitching moment has been found in two cases for complete models; it would appear to be quite appreciable but not of first importance as compared with the rolling and yawing moments due to rolling. An actual determination of these two latter moments for a complete model would appear to be an essential for any accurate estimation of the spinning properties of an aeroplane. The moments have now been measured for a number of aeroplanes—and are presented later in the form of vector diagrams but it is not yet possible to predict them with any certainty. We must not omit some reference in passing to the pitching inertia moment which is due to the rolling motion not being about a principal axis of the aeroplane. It is the existence of this moment which makes possible the growth of the incidence in a spin to a value far greater than stalling incidence. The couple is a maximum at about 45° incidence for a given rate of rotation, but goes up as the square of the speed of rotation.

Of the forces and moments set up by the subsidiary motions we may dismiss at once those due to the yawing motion (wind axes): there is good reason for believing those effects to be inappreciable.

The pitching motion is important in giving rise to a pitching moment which affects the balance of pitching couples. We know from ordinary wind tunnel tests in which a simple pitching motion is given to the model that with the rates of pitch found in spinning, pitching moment due to pitching may be appreciable, but so far we have no data as to this moment under actual spinning conditions. The rate of pitch is also important as being a factor determining the sign and magnitude of the yawing couple about the body axis due to inertia. This couple also depends as to sign and magnitude on the difference $A-B$ of the inertias about the longitudinal and transverse axes and may reach a magnitude of the same order as that of the rudder power.

Sideslip is important in its effects even when small. For example, a sideslip of about 10° (without rolling) will give rise to a rolling moment large enough to balance the biggest unstable rolling moment ever found in tests without sideslip on the rolling balance; from which it may be gathered that deductions as to the spinning properties of wings, based on their auto-rotative or rolling properties without reference to sideslip, are practically meaningless. This is a point we enlarge upon in a later section. The aerodynamic yawing moment due to sideslip is not usually great, but may, nevertheless, be of some importance. It may act in either sense for a given direction of sideslip: for aeroplanes with large and effective fin area aft, the moment may be expected to act in the sense to bring the aeroplane "into the wind," but if the body is short and not deep aft the sense may be reversed.

Rolling and yawing moments due to sideslip have been determined for a number of complete models, but only in one case (which was for wings alone) have moments due to sideslip been measured in the presence of a rolling motion. It was then found that the effects of sideslip and roll were not additive after the stall, the error being at times considerable. Some recent experiments by D. H. Williams on the pressure distribution over a yawed aerofoil have, however, enabled the experiments to be looked at in a rather different light, by which it is seen that the discrepancy is in reality not nearly as great as was thought. Williams's experiments enable the effect of sideslip on rolling moment (lv) to be estimated, taking into account the variation of incidence along the span which occurs as the result of the rolling motion. If this is done results are brought into much better agreement. We may note that the outstanding feature of the results is that a rolling motion sometimes results in a very considerable reduction in effective lv, due chiefly to the reduction of incidence of the rising wing tips. The available data do not, unfortunately, enable the comparison to be extended above 42° incidence or to very high values of the rate of rotation.

We have seen that sideslip is connected to rate of pitch upon which the yawing inertia depends. It is now quite easy to trace the connection between the nature of the results given by a rolling balance test (without sideslip) and the yawing inertia couple. For, if the rolling balance shows unstable rolling moments of any appreciable magnitude, they must be balanced in a spin by some inward sideslip, and *vice versa*. It is therefore clear that the sign and magnitude of the yawing inertia couple can be regarded as depending in the first instance on the nature of the rolling couples given by the rolling balance tests, as well, of course, as on the inertias of the aeroplane.

The Question of Recovery.—Since we wish to review our data, more especially from the point of view of recovery from a spin, it would be as well if we first gave some consideration to the question as to the kind of applied moment likely to be of most value in stopping the spinning motion. If we do this we may get some indication as to where best to apply the moment. For if we have recourse to some form of wing tip control such as ailerons in one or other of their forms,

or interceptors, we shall in general get a moment which is a combination of both rolling and yawing moments, with very little pitching moment. On the other hand, a control at the tail would give us a pitching moment from the elevators (with possibly some yawing moment at the same time due to variation of shielding of the rudder caused by their movement) ; and/or practically a pure body yawing moment due to rudder.

Fortunately we now have theoretical work backed by some full-scale experiments bearing on this question. Some recent theoretical work by Bryant and Miss Jones on the stability and mechanism of recovery from a spin has led to interesting and important conclusions. Starting from two steady spins on the Bristol Fighter, of which actual records had been obtained, they calculated the stability of the motion and also the effects, for the first few seconds, of rolling, pitching and yawing couples (referred to body axes) separately applied against the spin.

The two spins were a " steep " spin at 32.4° incidence, and a " flat " spin at incidence 53°. As regards stability all that can be said is that marked instability was found for the first spin, such that in a very short time the incidence changed so much that the assumption of constant derivatives was manifestly invalid, while the flat spin was found to be stable; it is not yet deduced, however, that this stability is characteristic of the flatter spins and that instability characterises those at lower incidences.

In considering the effectiveness of the controls in recovery, Bryant and Miss Jones draw attention to the mutual influence of incidence, sideslip and rotation, which has an important bearing on the results obtained. They point out that for a right-hand spin, for example:—

> Reduction in rate of roll produces negative (outward) sideslip, which, in turn, tends to keep up the rate of roll.
>
> Reduction of incidence also produces negative sideslip.
>
> Reduction of rate of yaw produces positive (inward) sideslip.
>
> Negative sideslip produces an increase in incidence.

These influences, which are purely dynamic, as distinct from aerodynamic, are found to have a big delaying effect on the action of either a rolling moment or a pitching moment in stopping a spin, and it is concluded that the rudder is by far the most effective control for the purpose of recovery from an established spin. Ailerons are not likely to effect recovery by virtue of the rolling couple they can produce; but rather their influence in stopping or augmenting the spin will be governed by the yawing moment (body axes) due to them.

The elevators, if capable of applying a large enough pitching couple, will probably in general effect recovery, but they will always tend to set up another and faster spin. The reversal of the elevators is probably necessary, as lower incidences are reached in order to prevent relapse into a spin of opposite sign, and it undoubtedly accelerates recovery at such a stage; but it is not clear that the reversal invariably assists recovery during the flat spin stage, and some delay in moving the elevators down may conceivably help in certain circumstances.

We would therefore recommend pilots to apply full opposite rudder before easing the stick forward in recovering from prolonged spins which have tended to become flat.

In Fig. 2 we reproduce the curves obtained by Bryant and Miss Jones for the initial stages of the response to a given rolling, pitching, or yawing couple in a flat spin. Alongside we also give curves recently obtained for the motion of a Bristol Fighter in a spin at an incidence of 43° after application of either fully opposite rudder or elevators. The full-scale results generally bear out strikingly the conclusions based on theoretical work. Application of opposite elevators causes only a very temporary reduction of rate of roll (body axes) followed by a considerable increase; at the same time there is a slight, though steady, rise in

the rate of yaw r'. The rudder, on the other hand, gives a steady reduction in rate of yaw; but reduction in rate of roll is not marked till after about five seconds, when it becomes rapid.

Model Experiments

The chief developments on the model experimental side of spinning research in recent years have been the continuance of wind tunnel work on complete models on the rolling and the three-force-and-moment balances, and the development of the free flight method of experiment with models dropped from a considerable

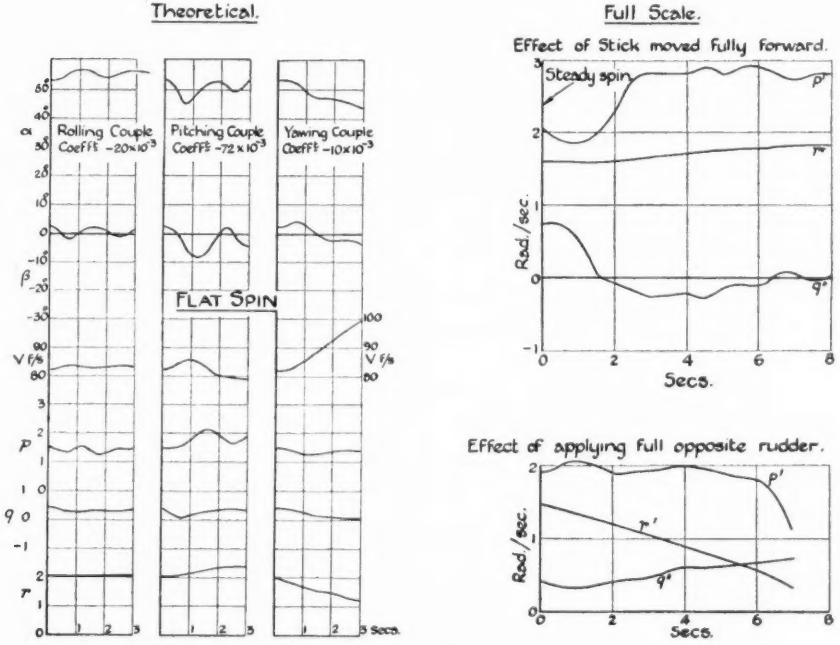


FIG. 2.

The effect of applying a rolling, pitching, or yawing couple against a spin.

height. On the rolling balance there has been the important addition of measurement of yawing moment due to rolling, no data on which were available for a complete model at the time Gates and Bryant wrote their paper. Further, a considerable amount of work has been done both in the tunnel and in the free flight model experiments on the effect of various modifications to an aeroplane, chiefly to the tail unit, but including the effect of seaplane floats, differential and floating ailerons and "interceptors" in a spin. We shall deal with the tunnel experiments first, as a number of the dropping model tests were made later as check tests on effects previously found in the tunnel.

A word or two may here be advisable on the distinct functions of the two types of model experiment, the horizontal tunnel experiment, in which the model is either held fixed or its motion constrained; and the free flight test, made either by dropping the model through still air, or in the vertical tunnel where the "fall" may be prolonged indefinitely.

The horizontal tunnel experiments in which the model is held are valuable chiefly in giving us the means whereby an analysis of the forces and moments acting in a spin can be made. They are of great assistance in finding out not

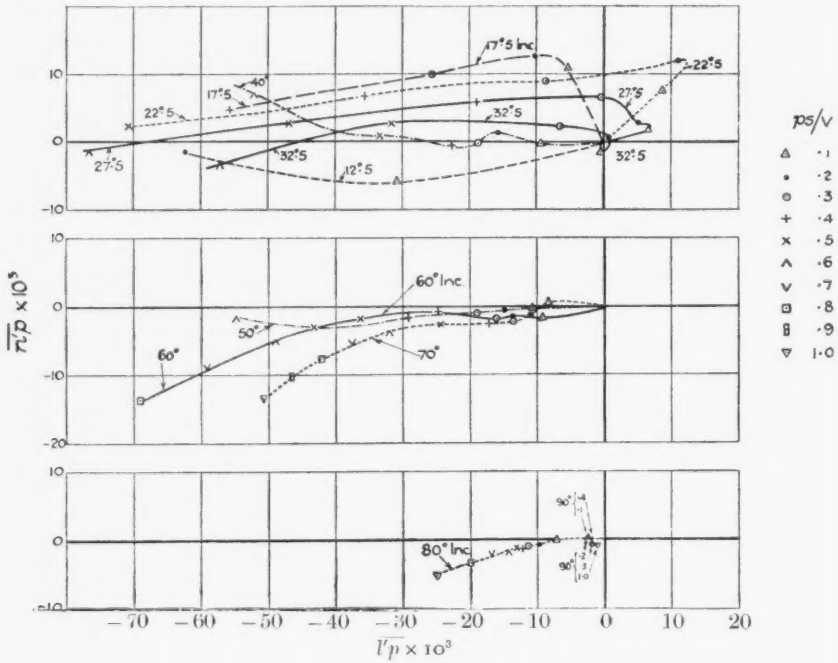


FIG. 3.

Rolling vector diagram for model R.A.F. 15 monoplane up to 90° incidence.

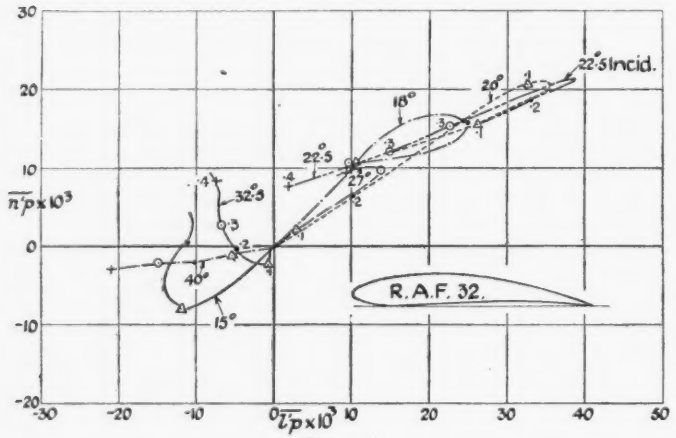
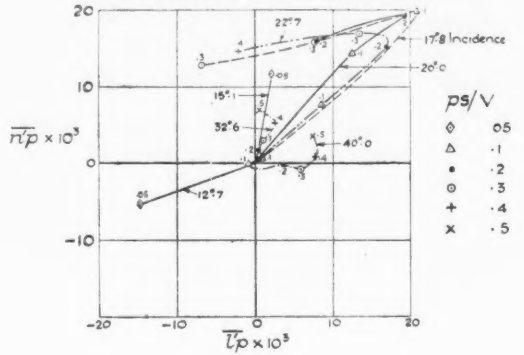


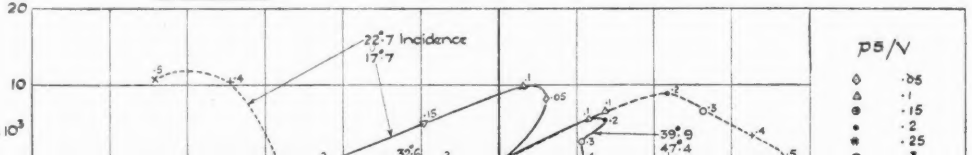
FIG. 4.

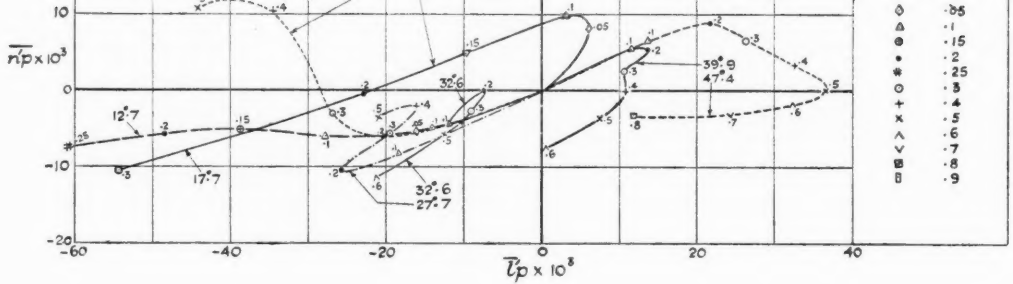
Rolling vector diagram for R.A.F. 32 model monoplane.

No Slots



Tip Slots.





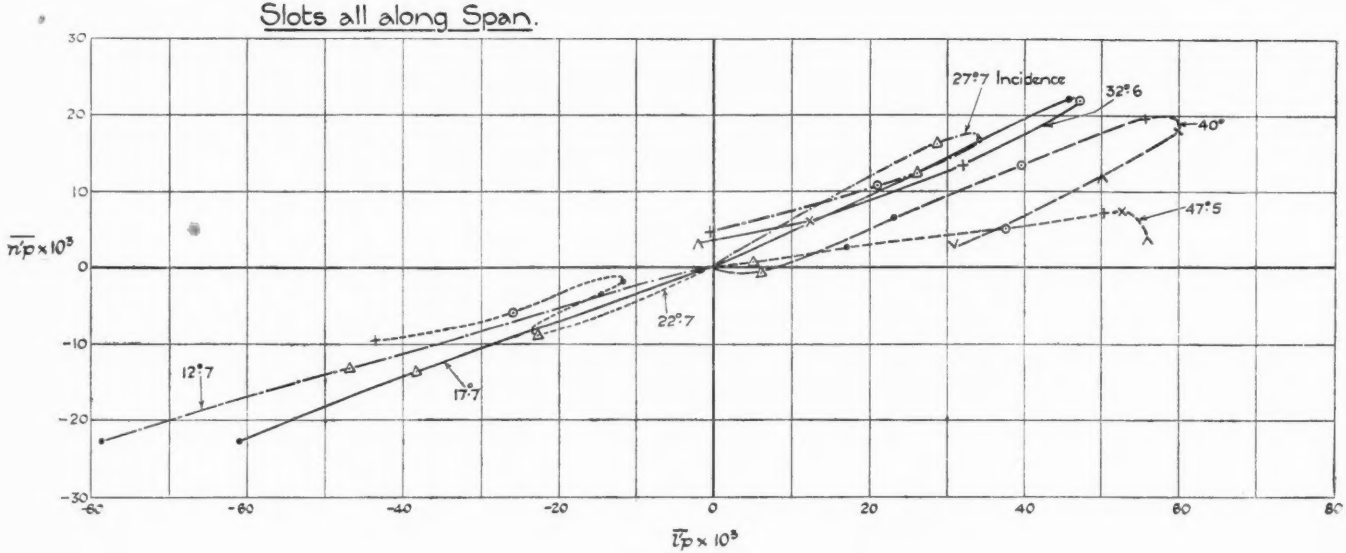


FIG. 6.
Rolling vector diagrams for R.A.F. 31 model biplane with and without slots.

only what particular features in a machine are good or bad, but exactly why they are good or bad. Further, they afford data on which to base calculations of the equilibrium in a spin, and these serve to indicate the magnitude of the spinning problem, the possibility of making machines safe without any radical alterations, and generally provide a rational basis of design against spinning trouble.

The free flight model experiments, on the other hand, are very useful either in checking the behaviour of a particular design in a spin, or in observing the overall effect of any modification which may have been made. When the vertical tunnel now under construction at Farnborough is completed it should be a fairly simple matter to test the spinning and recovery properties of any new aeroplane before it is flown, and it should soon become evident whether there is any scale effect of sufficient magnitude to cast doubt on its reliability as an indicator of the safety of an aeroplane in a spin.

Horizontal Wind Tunnel Tests

Rolling and Yawing Moments Due to Wings when Rolling.—Experiments have now been made on the rolling properties of a fair number of wings of different section and biplanes of different arrangement. A systematic investigation on the effects of gap and stagger was made some time ago, the results of which were given by Gates and Bryant in their paper. The results applying to stagger when the gap/chord ratio is unity, are here re-presented in slightly different form along with data for other wing sections and arrangements in Figs. 3-8. The

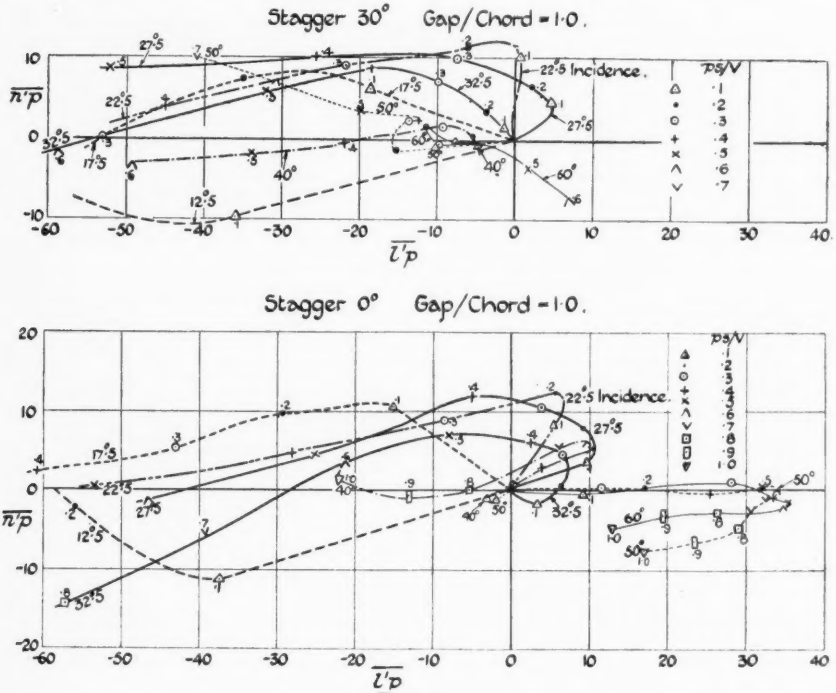


FIG. 5.

Rolling vector diagrams for R.A.F. 15 model biplane with 0° and 30° stagger.

diagrams take the form of vector diagrams (chord axes) of yawing moment plotted against rolling moment, there being one curve for each incidence, while speed of rotation, ps/V, is marked along the curves or indicated by a series of points to which a key is given. One case of a biplane with and without slots is included, namely, R.A.F.31 with tip slots and slots all along the span. It is not easy to grasp the full significance of such diagrams in relation to spinning unless one has some experience of calculations on the balance of forces and moments in a spin. Return will be made to this point later, but in the meantime

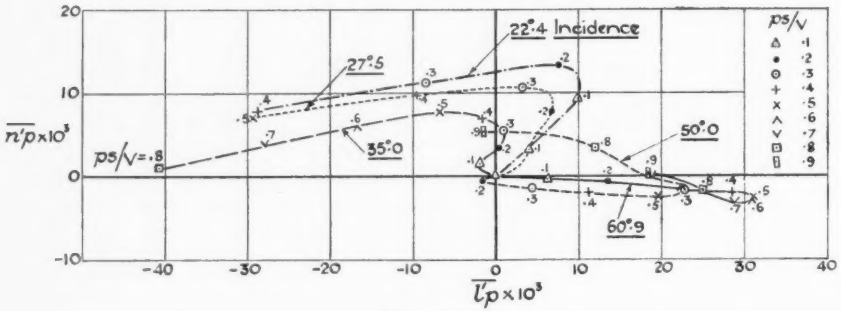


FIG. 7.
Rolling vector diagram for wings of typical seaplane (see Fig. 9).

it may be observed that thick wings appear to give greater positive values of both rolling and yawing moments than thin wings, and in one case, namely that of the single-seater fighter wings, one gets the combination of high positive values of $l'p$ and $n'p$ at high values of incidence and ps/v, thus tending, as will be seen later, since A-B is positive, to make easier the attainment of equilibrium

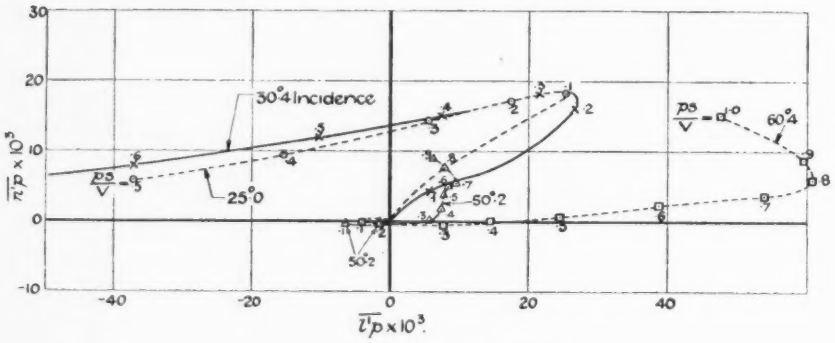


FIG. 8.
Rolling vector diagram for wings of single-seater fighter (see Fig. 11).

conditions in a fast flat spin. Slots give an increase in the values of the positive rolling moments, but there is a delay in the incidence and rate of rotation for which positive values are first obtained; this, of course, is what gives them their value as regards low speed stability. The biplane with tip slots shows

a considerable reduction in the maximum value of positive yawing moments as compared with the unslotted biplane, but when the slots are extended along the whole span these moments rise to their former maximum values at, however, increased incidence. The foregoing remarks apply to slots which are fixed open and may require some modification in the case of automatic slots, which have often been observed to remain closed, or nearly so, once a spin has developed.

Rolling Vector Diagrams for Complete Models.—We now come to the diagram which is, perhaps, the most important of all for the purpose of carrying out spinning calculations, and it is one in which our present state of knowledge can only be obtained with reliable accuracy by direct experiment. In all we have diagrams for seven aeroplanes (see Figs. 9-17):—

Typical Seaplane	Single Seater Fighter	original form.
Typical Landplane	,, ,,	with lengthened body.
Hawker Hornbill	,, ,,	with deepened body.
" Bantam."		

The typical landplane is, strictly, the typical seaplane without floats, the effect of the undercarriage being neglected. Actually also, the landplane had a slightly

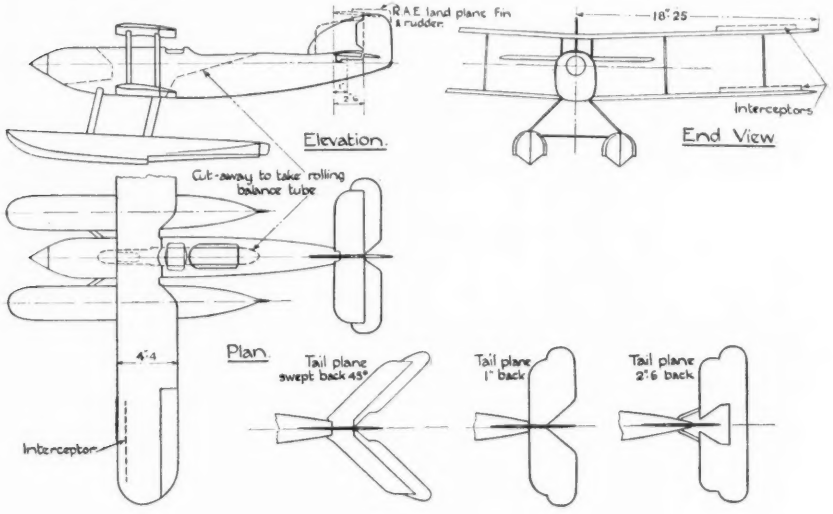


FIG. 9.
General arrangement of typical seaplane.

different rudder from the seaplane, but model tests indicated that the differences were slight. In all cases except that of the " Bantam " we have data for the wings alone (Figs. 7, 8 & 15), so that it is possible by subtraction to find the effective contribution which the body makes to the rolling and yawing moments due to rolling. And since the rolling moments are referred to body axes any contribution which the body makes can only be of the nature of an interference effect. As the examples given in Figs. 7-15, for wings only and complete model, show, this effect may be sometimes positive and sometimes negative and also sometimes of fairly large magnitude. With the limited data obtained we have not so far discovered anything systematic in the rolling moment due to body; which makes for unreliability in any estimated vector diagram based on wing and body data separately. Yawing moments (body axes) due to the original lengthened

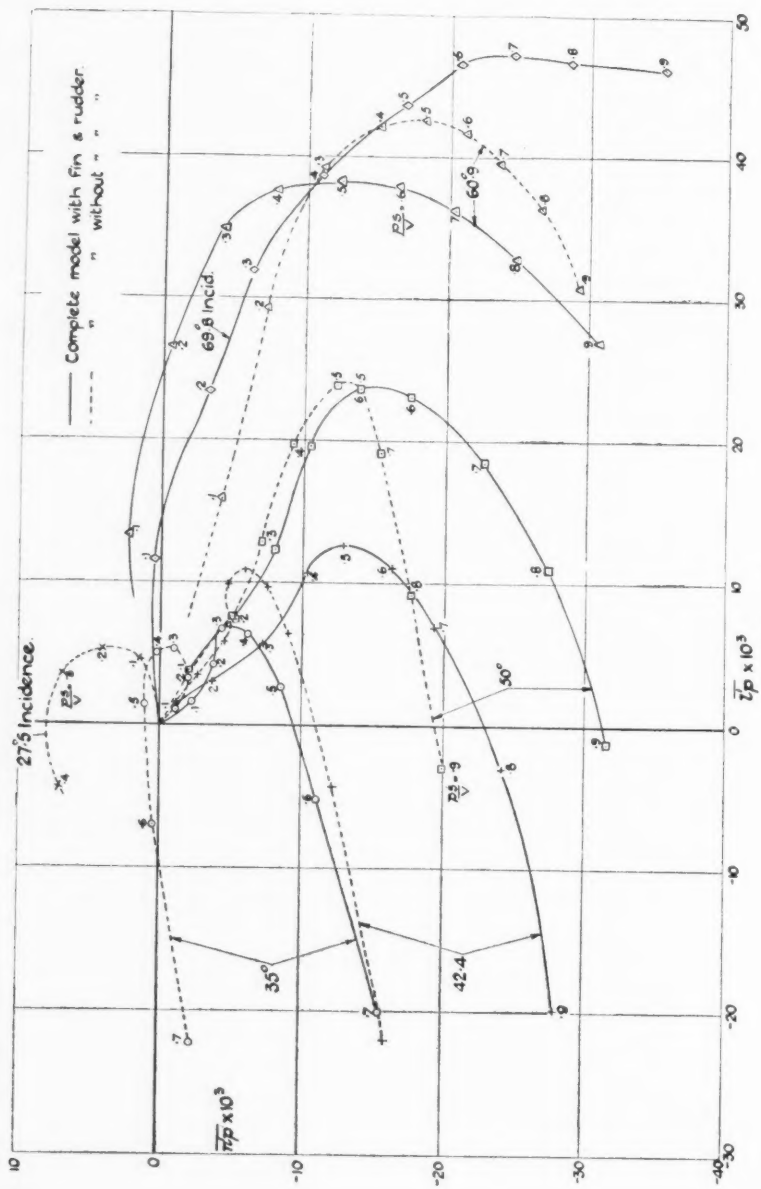


FIG. 10.
Rolling vector diagram for typical seaplane.

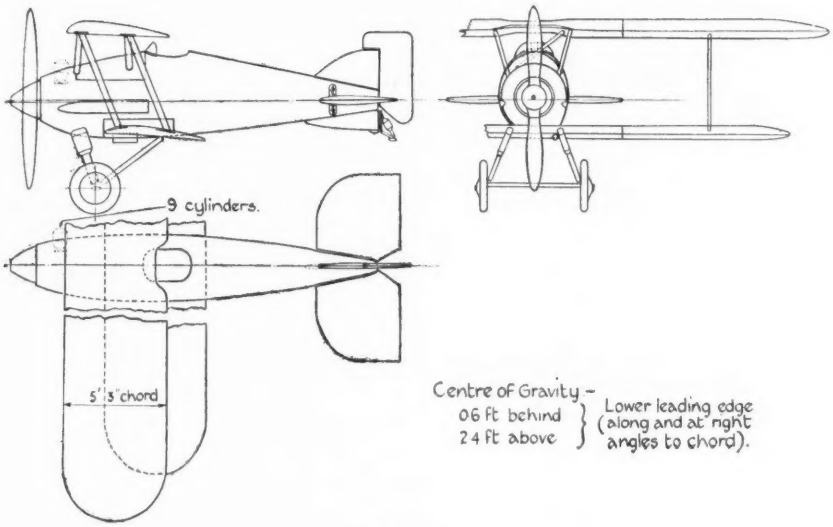


FIG. 11.
General arrangement of single-seater fighter.

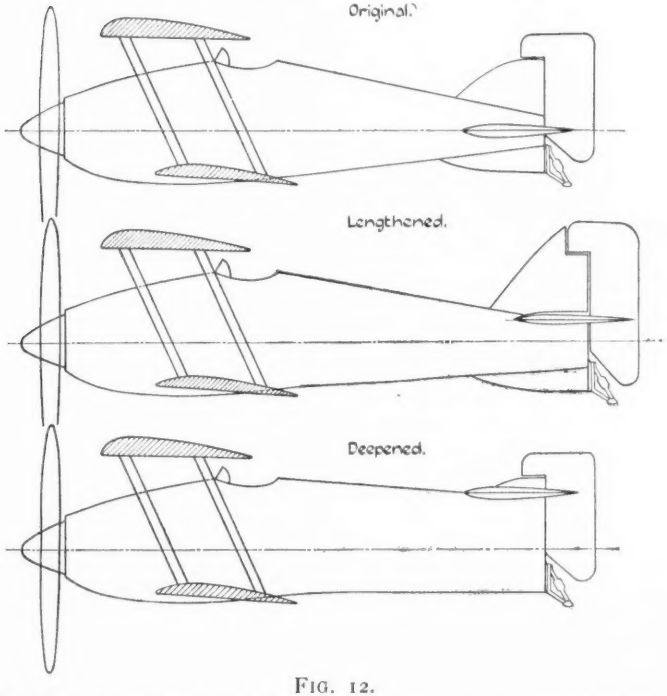


FIG. 12.
Original, lengthened and deepened bodies of single-seater fighter.

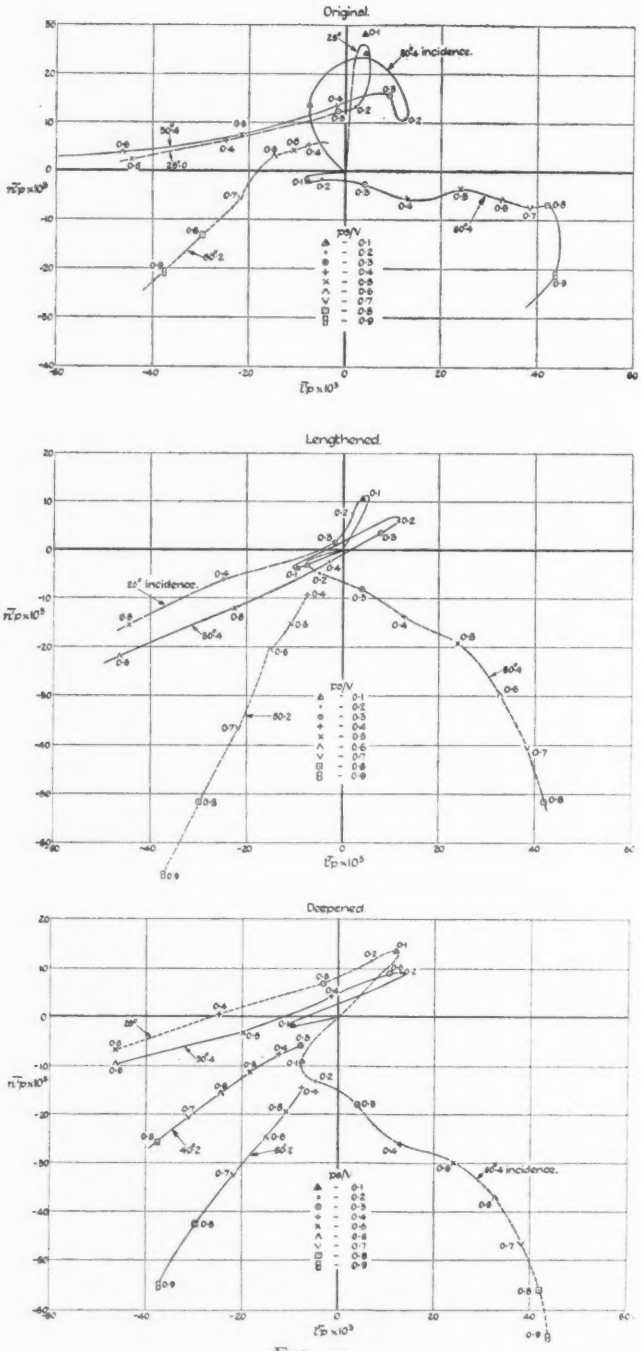


FIG. 13.

Rolling vector diagrams for single-seater fighter with original, lengthened and deepened bodies.

and deepened bodies of the single-seater fighter are plotted against ps/V in Fig. 18.

Sideslip Vector Diagrams.—We have previously mentioned that the available spinning data on models mostly apply to the effect of one variable at a time and that only in one case has the combined effect of sideslip and roll been checked against the sum of their separate effects, with what may now be considered a fairly satisfactory result.

We have then to take such data as there are for various aeroplanes for sideslip unaccompanied by rolling and in applying them to spinning calculations to modify them to the best of our ability according to the angle of incidence and rate of rotation we are considering. We have seen, too, that such modifications will in general take the form of a reduction in lv, which reduction is probably the greater at high rates of rotation.

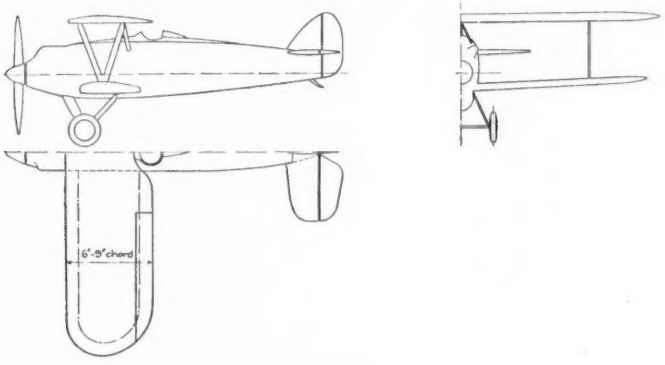


FIG. 14.

General arrangement of Hawker "Hornbill."

A number of rolling-yawing moment vector diagrams for sideslip were given for various aeroplanes in the Report of the Stability and Control Panel, R. & M. 1000. These included the following:

Standard Avro.	"Bantam."
Bristol Fighter 2b.	"Atalanta" N4 (Flying Boat).
S.E.5a.	

We are now able to add diagrams for the typical seaplane (Fig 19) with and without floats and the single-seater fighter fitted with the original, lengthened and deepened bodies (Fig. 20). In all these cases the range of incidence has been extended upwards from the maximum of 36° or 40° for the earlier cases to 60° incidence. It is seen that while there is little variation of $l'v$ with incidence over the spinning range for the seaplane with or without floats, there is a steady increase in $l'v$ with incidence for the three fighters. This, however, as we have seen, does not necessarily apply when there is rolling combined with sideslip. The sense of yawing moments for the seaplane and landplane is the same as for those machines listed above; but for the single seater fighter it will be observed that for both the original and lengthened bodies this sense is sometimes reversed.

Effect of Various Tail Modifications, etc., on Spinning Characteristics.—It has long been realised that while the phenomenon of the spin arises from the inherent properties of the wings, difficulty in recovery results from a falling off in the efficiency of the tail organs in the spinning condition. For instance, above

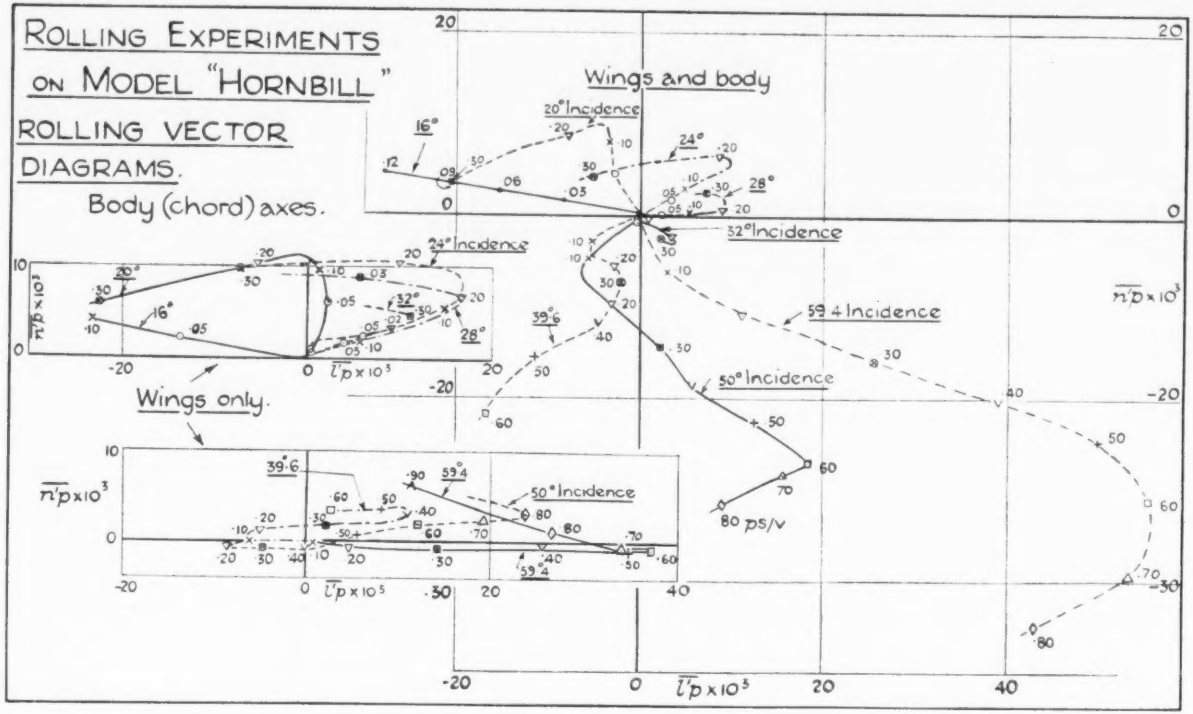


FIG. 15.

Rolling vector diagram for "Hornbill" wings and body, and wings alone.

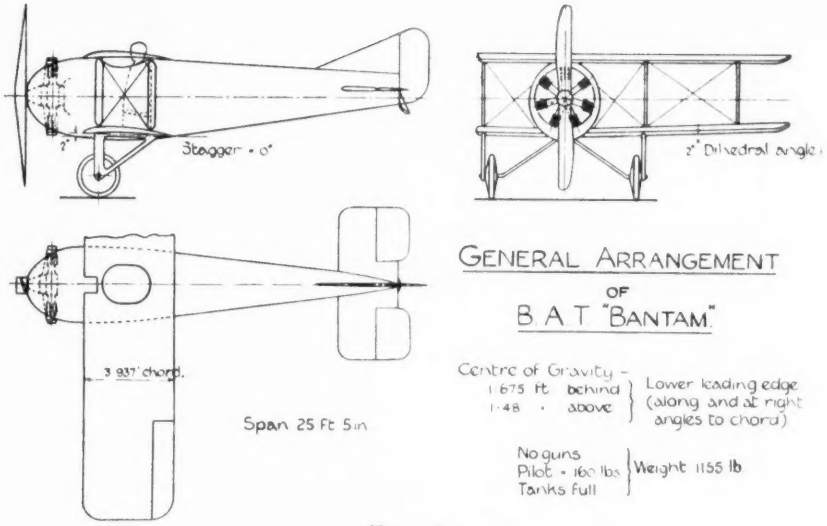


FIG. 16.
General arrangement of "Bantam."

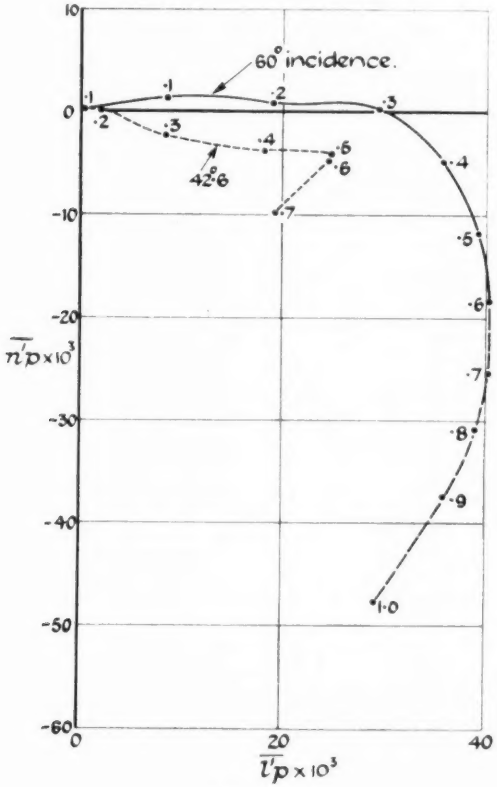


FIG. 17.
Rolling vector diagram for "Bantam."

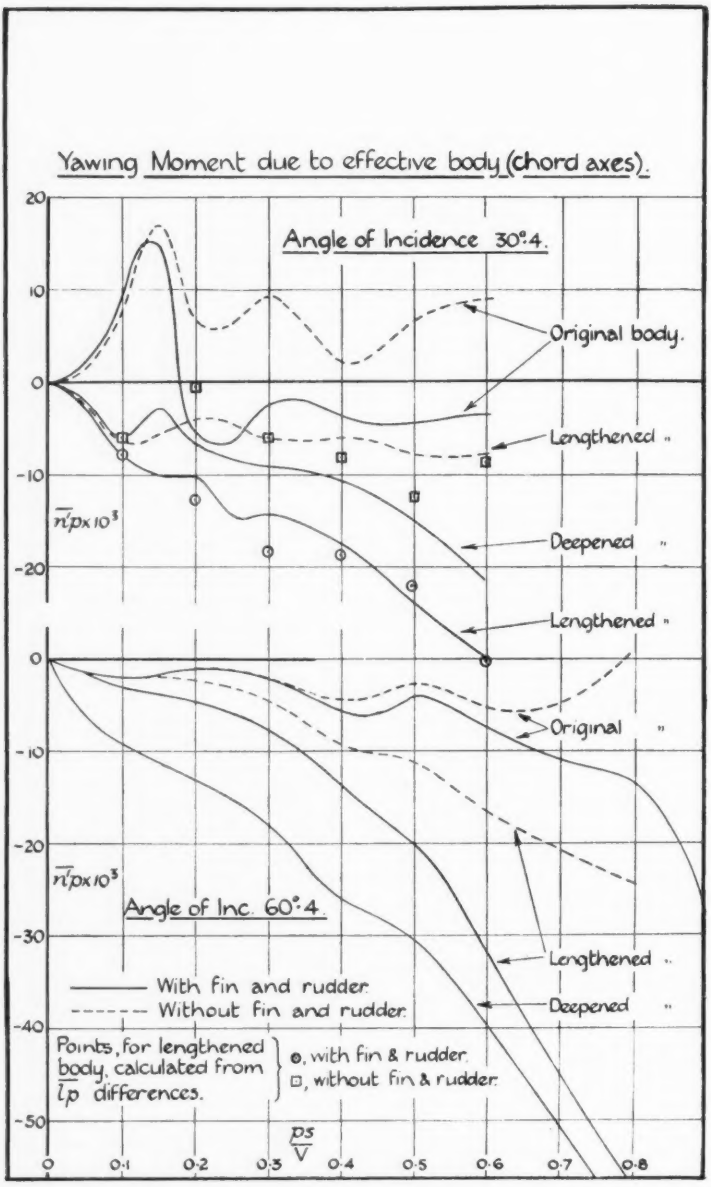


FIG. 18.

Yawing moment due to effective body for original, lengthened and deepened fighters.

the stall the slope of the pitching moment-incidence curve generally falls off as the incidence increases and may become practically flat or even show a slight reversal of slope in the region of 45° incidence, which is about the angle at which the pitching inertia couple reaches a maximum for a given speed of rotation. At the same time there is a steady diminution in elevator control as the angle of incidence increases. It is not difficult, then, to visualise a condition of affairs in which, once spinning has been prompted by the auto-rotative tendency of the wings at the stall, it is possible for the incidence to be carried by the pitching inertia couple far beyond that at which trim would normally obtain; and that once this has happened the reduced power of the elevators might suffice for no more than slightly to modify the spin. But with the early data available it was not easy to understand how balance of yawing moments was possible at these high incidences. At that time data on the effectiveness of body fin and rudder

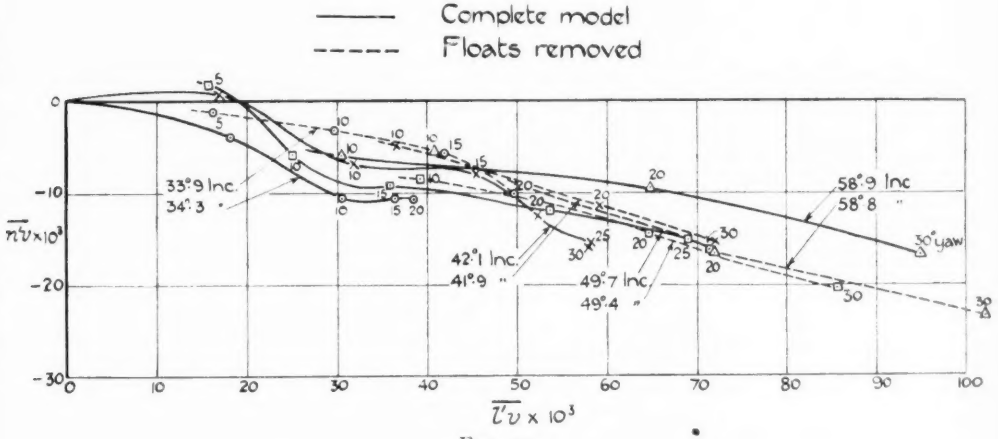


FIG. 19.

Sideslip vector diagram for typical seaplane.

did not extend to incidences much beyond the stall and their effectiveness at higher incidences could only be found by extrapolation. New light was thrown on the matter by experiments on a model of the " Bantam " aeroplane, in which it was found that as the spin became flatter the effectiveness of the fin and rudder fell off till at 60° incidence their effect was reversed. Sufficient was done in these experiments to establish that it was the tailplane which was responsible for this phenomenon. If the tailplane were removed the fin and rudder were just about as effective as when supported on a thin rod and rotated in correct relative position; the wings had some effect on the fin and rudder, but the body very little once the rotation had developed. Even the moving over of the elevators for recovery from the hard up to the hard down position produced an appreciable decrease in fin and rudder moment due to increased shielding.

This question of the interference of tailplane on fin and rudder has been studied further in some more recent experiments made on the typical twin-float seaplane previously mentioned. The primary object of the experiments had been to study the effect of floats on those aerodynamic characteristics of most importance in spinning, but as this reversal in fin and rudder effect at high incidences was again found it was decided to try the effect of a number of modifications to the shape and position of the tailplane. These are mostly shown by

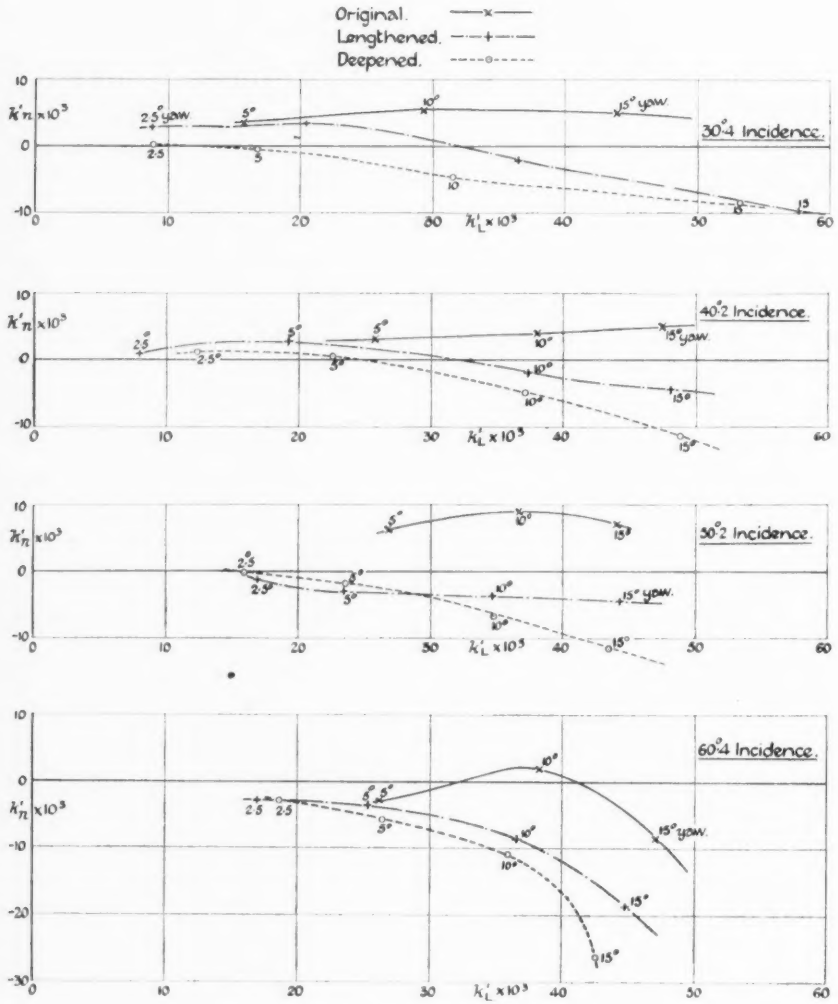


FIG. 20.

Sideslip vector diagrams for single-seater fighters.

Fig. 9 and their order of merit as regards the moment given by the fin and rudder is set out below.

ORDER OF MERIT OF MOMENTS DUE TO FIN AND RUDDER.

Tailplane on top of fin and rudder	Not much difference between these three.
Tailplane swept back 45°; elevators + 90°	
Tailplane removed	
Tailplane swept back 45°; elevators + 45°	About $\frac{2}{3}$ of possible improvement obtained.
Tailplane swept back 45°; elevators 0°	
Tail moved back 2.6in. (the equivalent of 45° sweepback)	
Tailplane dihedral + 20° (Tail bent upwards)	
Tailplane moved back 1in. (15in. full scale)	
Tailplane cut away $\frac{1}{4}$in. at body	
Tailplane in original position	
Tailplane dihedral − 20°	

It should be realised that this order of merit does not necessarily apply to *recovery* from a spin, in which rudder power is an important factor, although it may be stated that the order of merit for rudder power, so far as it was found, does not differ much from that given above (see Fig. 22).

The moment about the spinning axis given by the fin and rudder when the model is rotating is plotted against speed of rotation for the various cases in Fig. 21. For the original fin and rudder it will be seen that at 60° incidence, as soon as the rotation starts the moment becomes positive and rises sharply to a value close on 5 (comparing with a rudder control value of round about 10 for normal flight). As the speed of rotation increases the moment gradually falls till it becomes zero at $ps/V = 0.8$. Here it is seen that *the loss in fin and rudder moment due to the presence of the tailplane is well over 20, or more than twice the rudder control usually required of an aeroplane.*

There is a great contrast when we turn to the case of fin and rudder placed on top of the tailplane. Here the moment due to fin and rudder is slightly greater at high values of ps/V than when the tailplane is removed. This result gives some ground for the expectation, which is fulfilled, that a positive dihedral angle (tailplane bent upwards) would be good and a negative dihedral bad.

Sweep-back of the tailplane, as well as moving it bodily back are both good, giving roughly the same results so long as the movements of the centre of area are equal. A sweep-back of 45° or a bodily movement backwards of 2.6in. on the model (3ft. 3in. full scale), gave about two-thirds of what may be regarded as the total improvement possible for a given fin and rudder. With elevators set down at 45° and 90° on the swept-back tailplane considerable additions to fin and rudder moment were obtained, the addition for 90° elevators bringing the moment at large ps/V probably well up to that given with the tailplane on top of the fin and rudder.

Cutting away the tailplane $\frac{1}{4}$in. ($3\frac{3}{4}$in. full scale) on each side of the body gave perhaps one-fifth of the total improvement possible, a result not quite as good as moving the tailplane back 1in. (15in. full scale).

Effect of Floats.—Generally speaking floats have been found to alter the characteristics of the machine in such a way as to render it more liable to the flat spin. Their effect on the differences of the inertia moments does not appear to be great, but they have important aerodynamic effects. Chief of these is their effect on pitching moment; they also at times produce a quite appreciable positive yawing moment when the machine is rolling. Above the stall they increase lift by about 10 per cent.

According to the model experiments, whereas without the floats the machine trims at the not unusual angle of incidence of 23.5° with elevators hard up, the

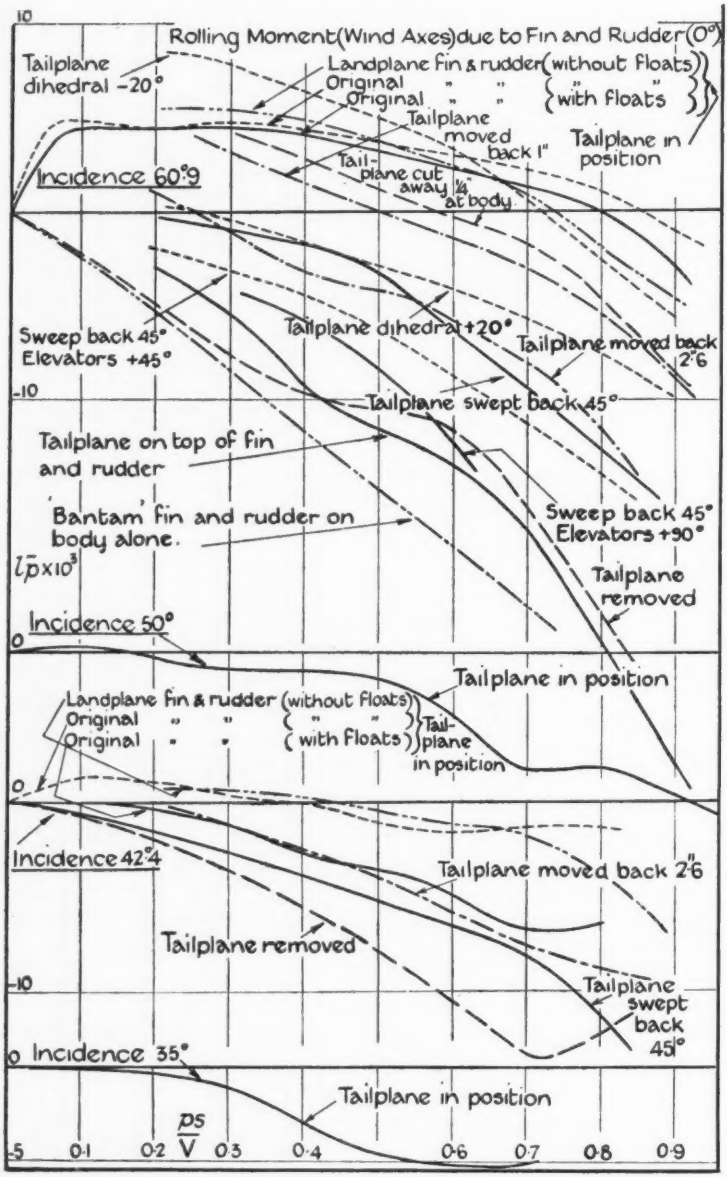


FIG. 21.

Rolling moment (wind axes) due to fin and rudder of typical seaplane with various modifications.

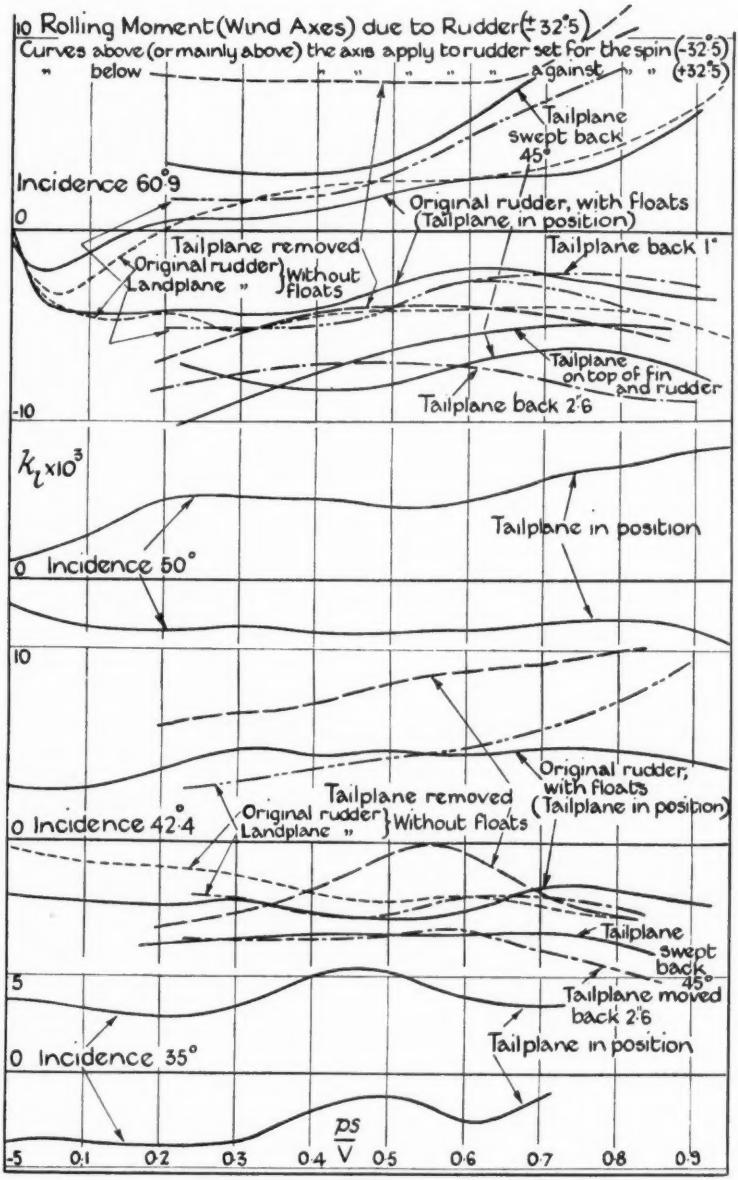

10 Rolling Moment (Wind Axes) due to Rudder (± 32°5)
Curves above (or mainly above) the axis apply to rudder set for the spin (-32°5)
" below " " " " " against " " (+32°5)
Tailplane swept back 45°
Incidence 60°9
0
Original rudder, with floats (Tailplane in position)
Tailplane removed
Original rudder } Without floats
Landplane "
Tailplane back 1°
Tailplane on top of fin and rudder
Tailplane back 2°6
-10
$k_l \times 10^3$
Tailplane in position
0 Incidence 50°
10
Original rudder, with floats (Tailplane in position)
Tailplane removed
Original rudder } Without floats
Landplane "
0 Incidence 42°4
Tailplane swept back 45°
5
Tailplane moved back 2°6
Tailplane in position
0 Incidence 35°
$\frac{pS}{V}$
-5 0·1 0·2 0·3 0·4 0·5 0·6 0·7 0·8 0·9

FIG. 22.

Rolling moment (wind axes) due to rudder of typical seaplane with modifications.

seaplane with floats trims at an angle as high as about 49°; recent full scale experiments show that there is no particular reason for doubting these figures. Of this large effect of floats on pitching moment rather less than two-thirds is due to the moment on the floats themselves, the remainder being an interference, or shielding, effect of floats on tailplane. Pitching moment due to floats reaches a maximum at an incidence of about 35°. There is also some reduction in elevator control due to floats.

Yawing moment (body axes) due to floats when rolling (Fig. 23) does not appear to be important till the incidence rises to the region of 60°, when it becomes positive and quickly rises with rate of rotation to about 5 between a ps/V of 0.3 and 0.4 Rolling moment (wind axes) due to floats is also generally positive and reaches a maximum value of 4 to 5 at 40° to 60° incidence. Added to this, rudder control appears to be somewhat reduced (see Fig. 22).

Thus we see that the general tendency of the effect of seaplane floats is to make conditions more favourable for the attainment of flat spins, and to reduce the control for coming out.

Differential Ailerons and Interceptors.—The experiments on the seaplane model were made the occasion of doing a few experiments on the effect of differential ailerons and interceptors on spinning, the results of which are plotted as vector diagrams in Fig. 24. Here, the rolling and yawing moments due to the differential ailerons and interceptors are each compared with the moments due to ordinary ailerons at different incidences and rates of rotation. The differential ailerons were assumed to move in such a way that while the up-going one had gone up to 45°, the other one had first gone down and then returned to 0°. The interceptor, it was assumed, projected fully out of the wing when the ailerons were at 20°, on the side of the upward aileron only.

Differential ailerons would appear to be fairly effective at the lowest incidence tested (42.4) when the rate of rotation is high, both as regards the provision of negative rolling and yawing moment. But their effectiveness falls off as the incidence increases and at about 60° incidence the control in roll is less than for ordinary ailerons, with, however, some reduction in positive yawing moment. These experiments indicate, therefore, that differential ailerons, while possibly of some use if the spin does not become flat are apparently of little use in a really flat spin.

Interceptors used in conjunction with the ailerons show some improvement in the control at the two lower angles of incidence, 42.4° and 50°, but at about 60° they make the control slightly worse than that of the ailerons by themselves. It would be interesting to have similar results for a model fitted with slots; these might well give much more promising results.

Rigged Up and Floating Ailerons.—Experiments on rigged up ailerons were made at 50° angle of incidence only, on the seaplane model; but a series of model rolling experiments has since been made at the Royal Aircraft Establishment in which the ailerons were allowed to float while the model was rolling. Rolling and yawing moments were measured both with the ailerons floating at the same angle and with the ailerons set over at equal positive and negative angles from the floating position.

Dealing first with the few N.P.L. experiments, the effect of rigging the ailerons up 45° is given in the middle vector diagram of Fig. 24. There is only a small effect on rolling and yawing moments until the value of ps/V rises above 0.6 when both moments become negative and increase with ps/V. The setting over of the ailerons by the large amount $\pm 45^c$ from the rigged up position produces a smaller rolling moment (chord axes) than the setting $\pm 20°$ from the zero position, but the positive yawing moment is reduced and becomes negative at high ps/V.

In the R.A.E. experiments the actual floating angle was found to be considerably less than the rigged up angle of the N.P.L. experiments. For example,

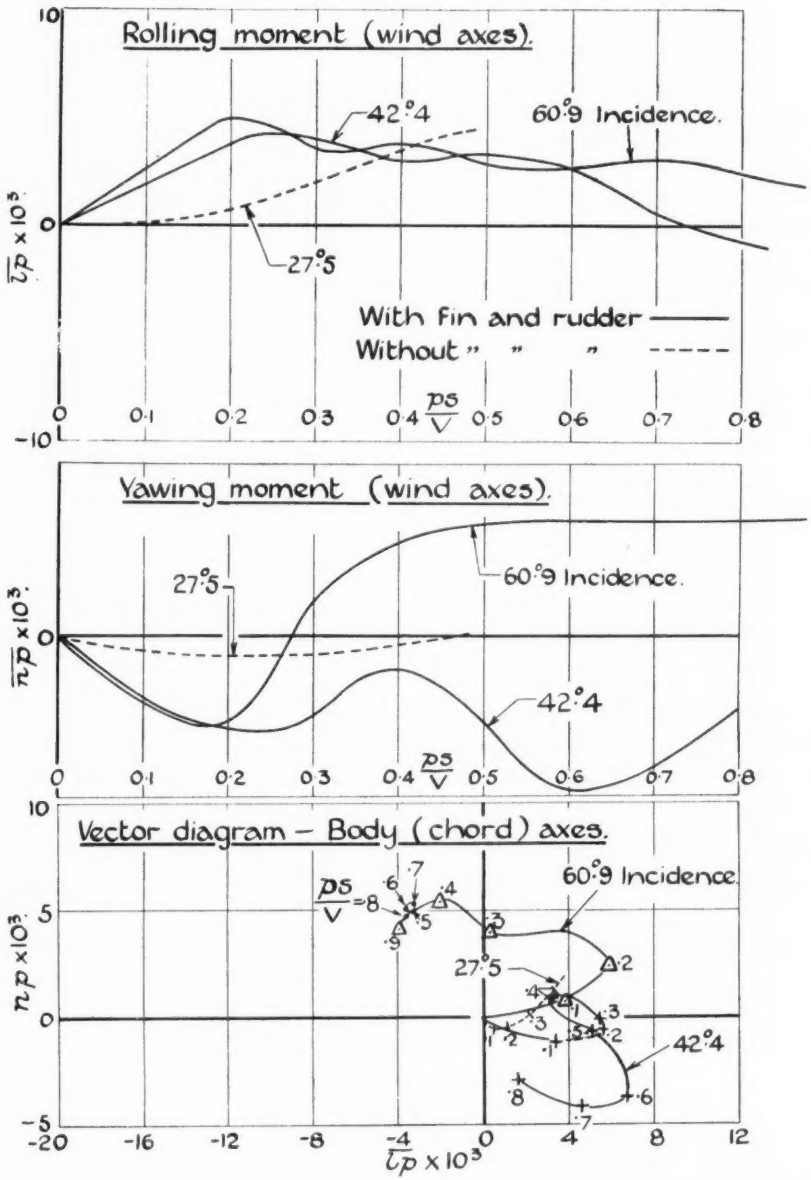


FIG. 23.

Rolling and yawing moments due to floats of typical seaplane.

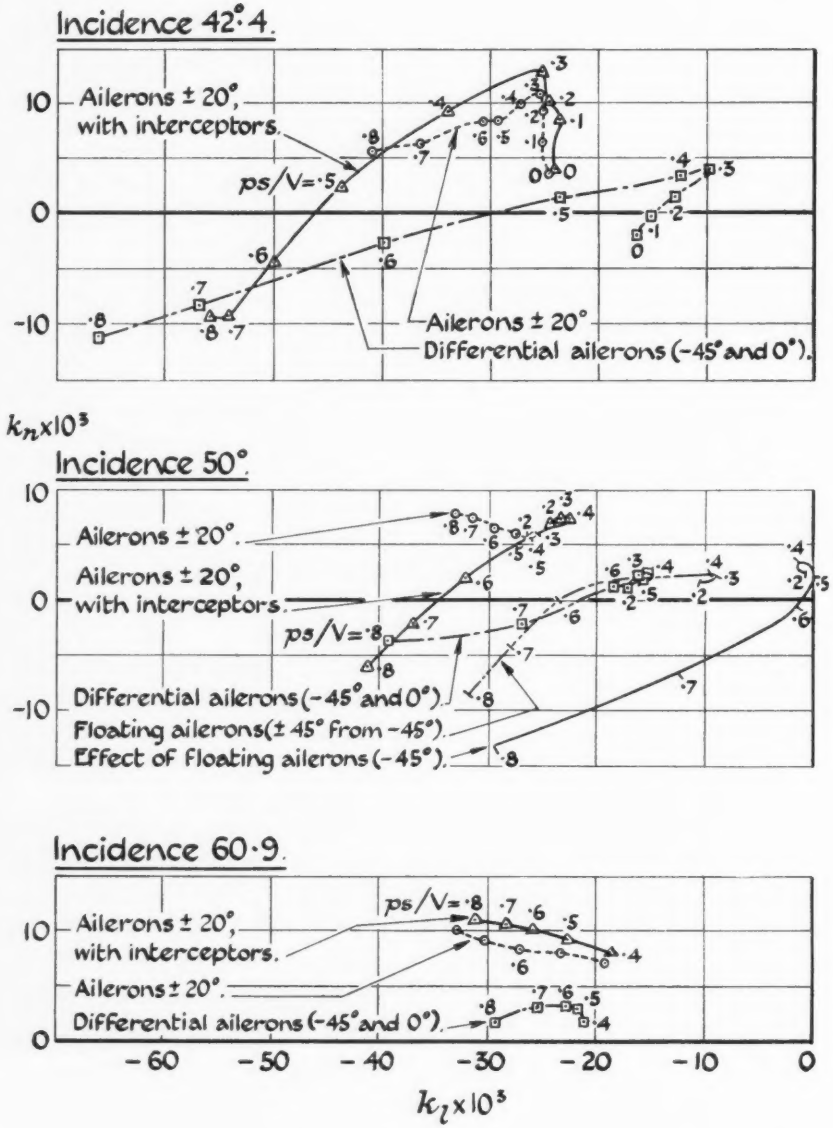


FIG. 24.

Vector diagrams for differential and floating ailerons and interceptors.

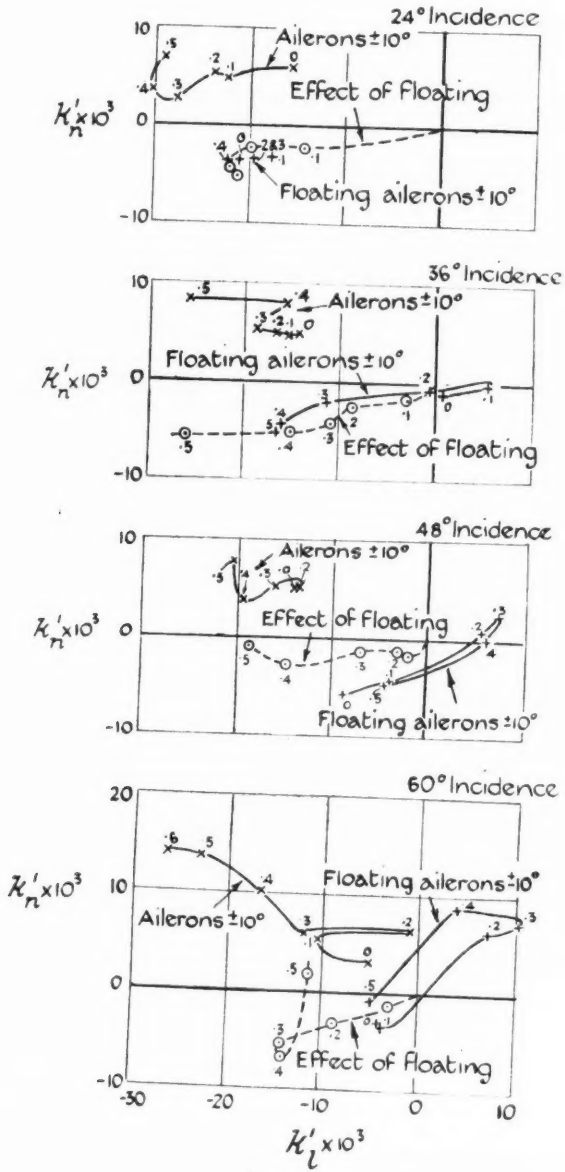


FIG. 25.
Vector diagrams for floating ailerons.

while in the N.P.L. experiments the ailerons were rigged up 45° at 50° incidence, at the R.A.E. the floating angle for 48° incidence was found to be 32°. This angle decreased to about 27° at $ps/V=0.5$, and increased when the ailerons were set over ±10°.

Vector diagrams plotted from the R.A.E. results are given in Fig. 25 for four angles of incidence from 24° to 60°. The difference in rolling and yawing moments due to floating the ailerons as well as the aileron control are again plotted to compare with the aileron control for the non-floating ailerons. Floating the ailerons always results in an appreciable negative rolling moment being set up, accompanied by negative yawing moments of somewhat small values on the whole. The control due to the floating ailerons is rather disappointing. There is at times a reversal in the rolling control while yawing moment is sometimes positive and sometimes negative. The general conclusion we draw from the model experiments is that floating ailerons may be expected to effect but little improvement as regards recovery from a spin.

Free Flight Model Experiments

During the last two or three years the technique of free flight model experiments has been undergoing continuous development at the R.A.E. In order to give some idea of the possibilities and limitations of these experiments, we shall describe the various methods which have been employed and indicate some of the difficulties encountered.

The crux of the whole experiment lies in the use of true dynamical models, if the results are to be regarded as quantitative data; this implies that the moments of inertia and total weight of the model must bear certain simple relations with those of the full-scale aeroplane. The construction of accurate models combining adequate strength with sufficiently low weight has proved to be no easy matter and accordingly many of the tests have, of necessity, taken the form of comparisons between modified versions of the same model. The models are constructed of balsa wood and ballasted with lead. This wood has an extremely low density but is by no means homogeneous, and, in consequence, calculated values of the moments of inertia of a model are unreliable; some method of measuring them had therefore to be devised. For this purpose the model is made to oscillate as a compound pendulum about knife edges parallel to the three axes and the relevant moments of inertia deduced from the observed times of swing. Owing to the relative lightness of an aeroplane with regard to its surface area a considerable virtual mass effect is present and it has been found necessary to perform the swinging tests in an atmosphere of low density; a chamber filled with hydrogen has proved satisfactory. A further reference to this experiment will be made in another section of this paper in connection with the determination of the moments of inertia of actual aeroplanes.

The spinning experiments consist essentially in observing the model in free flight under gravity. Up to the time of writing these experiments have been conducted in still air in the balloon shed at Farnborough; the model was released near the roof of the shed and allowed to fall freely until arrested by a net near the floor eighty feet below. This corresponded to a height drop of approximately fifteen hundred feet for the models used. In these circumstances it was not possible to represent the complete spinning manœuvre in one experiment unless the actual spin was of very short duration. Accordingly the models were launched with a series of spinning motions at the top of the shed with the controls set either to maintain a spin or to produce a recovery. Fig. 26 shows the apparatus employed. For some of the earlier experiments the models were launched in a stalled glide by means of ballistic pendulum and the preliminary stages of the manœuvre could be observed. In this way the available drop was used to the best advantage since it was possible to use the whole distance for a steady spin and also to observe the recovery from the motion and the incipient spin, in three

separate experiments. The main observations were the number of turns which could be counted and the total time of the drop. The attitude of the model was determined from photographs and in some cases cinema records were taken and the motion of the model subjected to a detailed analysis.

From dimensional considerations it can be seen that a $1/n$th scale model falling under gravity will move at a velocity which is $1/\sqrt{n}$ times that of the full-scale aeroplane. The tests are accordingly always carried out at a Reynolds

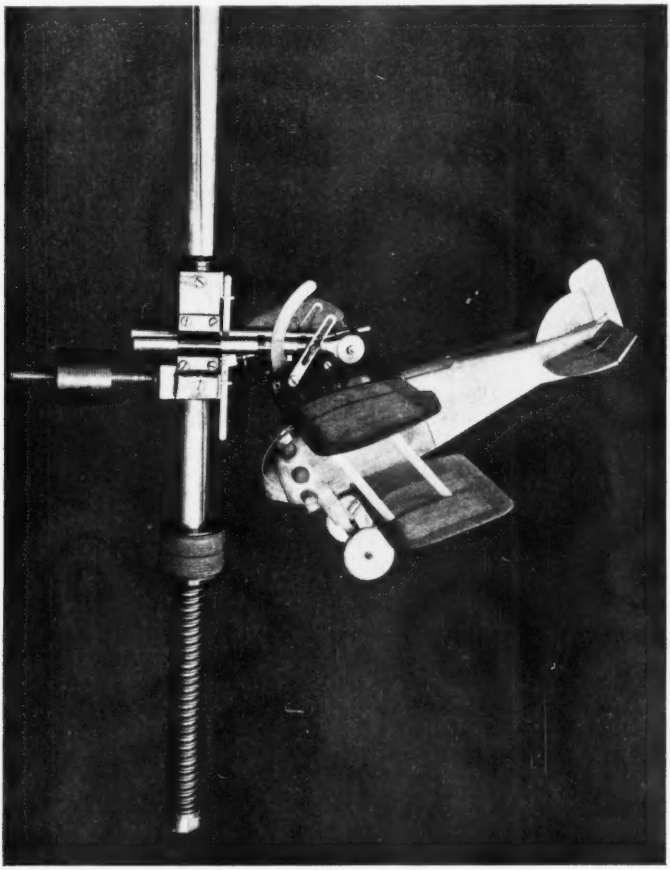


FIG. 26.
Rotary launching gear with model in position.

number which is $1/n\sqrt{n}$ times that at which the aeroplane operates, and there is no method of increasing it above this value, which is in practice about one-tenth that at which horizontal wind tunnel experiments are normally conducted. It is not easy to predict from existing data whether any serious scale effects are likely to be encountered in these circumstances. Experiments up to the present have been mainly of qualitative significance and it is unlikely that any appreciable errors will have arisen in the general conclusions which have been drawn. Before

much faith can be put in the quantitative data obtainable at the low Reynolds number a careful comparison between model results and full-scale experience will have to be made.

Experiments with Modified Tail Units.—Experiments have been performed with 1/15th scale models of the original single-seater fighter and 1/20th scale models of the Bristol Fighter with a view to improving their spinning properties by redesigning the tail unit. The experiments with the fighter models were mainly directed at investigating the spinning characteristics of the original and deepened models to see whether the overall effects of the deepened fuselage and raised tail plane would bear out the encouraging conclusions drawn from the wind tunnel work. The scope of the experiments was somewhat limited, but all results indicated that slower and steeper spins and very much more rapid recoveries might be expected from the deepened fighter.

When the original fighter model was launched in a fast flat spin with the controls set to maintain the motion it was found to complete fourteen turns of a spin at an incidence in the neighbourhood of 70°. On the other hand, if the model were launched in a slower motion or at lower incidence a totally different spin resulted, only six turns being completed in the same height at an incidence between 20° and 40°.

Owing to the limited duration of these spins there was no direct evidence that either would not in time change into the other; on the other hand, there was no reason to assume that both types of spin were not conditions of equilibrium although the faster type might never be obtained with a natural method of entry.

When the model was launched in the flat spin with rudder reversed it was observed to come out of the spin after five turns; on the other hand, a recovery from the steep type could be effected in half a turn with the same control setting. It is interesting to compare these results with full-scale experience. The original fighter completed three or four turns in a steep attitude before " flicking " into a flat spin.

Reversal of the controls in the first stage produced an immediate recovery, whereas if delayed until the spin were fully developed, recovery was only effected with great difficulty.

Experiments with the deepened fighter showed that the equilibrium of the flat spin could not be maintained; however the model was launched, a slow steep spin resulted. When the model was launched in a flat spin with the rudder set to oppose the motion, the direction of the spin was reversed after one turn. These results indicated a very appreciable improvement in design from the point of view of recovery from a prolonged spin, since the deepened model could recover with great rapidity from a spin both faster and flatter than it was ever likely to get into. The position of the centre of gravity corresponded to the condition of full military load for the full-scale machine.

Further tests were carried out with two other modifications of the original machine; the tail plane was raised above the original fuselage to the same position as that of the deepened model, the fin area being unchanged in one case and increased to give the same profile as the deepened model for the other.

In both cases the results were very similar to those with the deepened fighter. Spins at high incidence could not be obtained and recoveries were rapidly effected. The model with increased fin area was slightly superior to the other, but not quite as good as the deepened fighter both as regards rate of spin and rate of recovery.

A similar experiment was carried out with a 1/20th scale model of the Bristol Fighter to compare the effectiveness of an increase in rudder area of 85 per cent. in combination with several fin arrangements, with that obtainable by raising the tail plane towards the top of the standard rudder. The seven tail units compared are shown in Fig. 27.

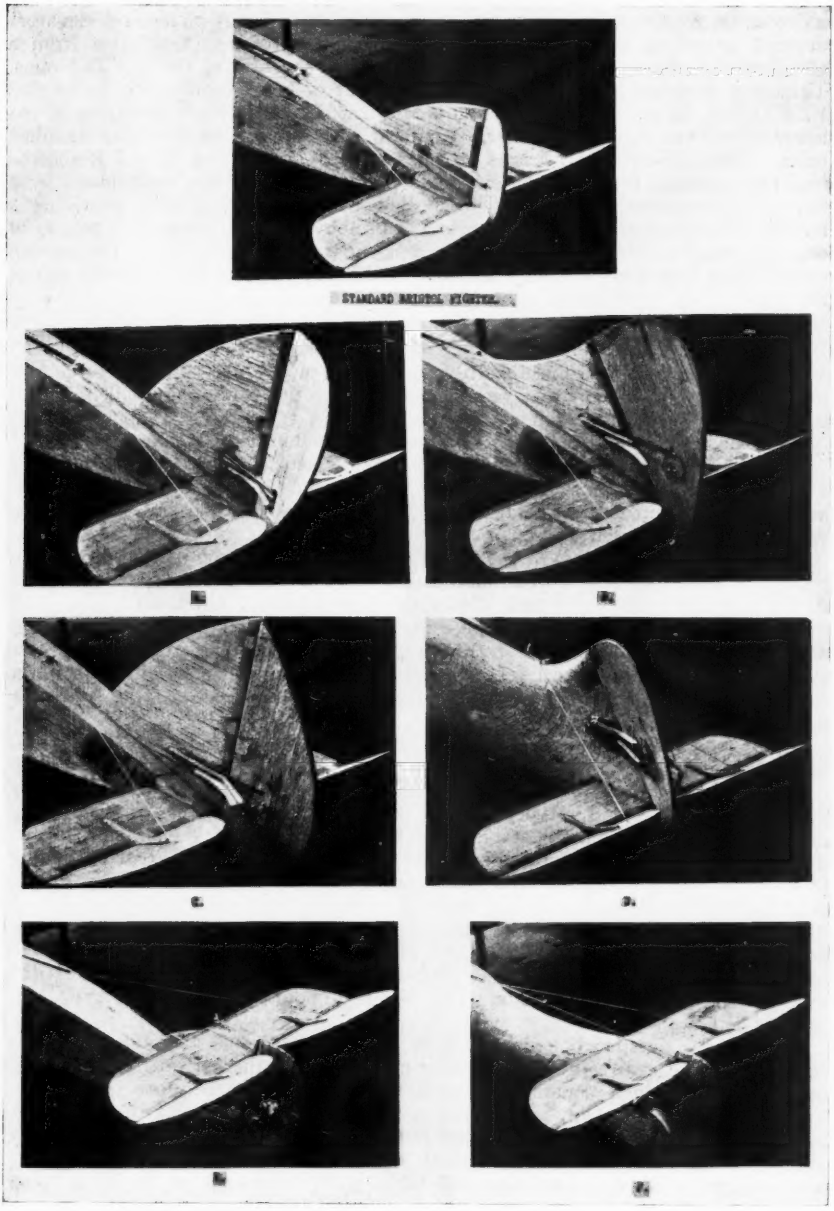


FIG. 27.
Anti spinning tail units for Bristol Fighter model.

It will be noticed that in all except A the additional rudder area is so disposed as to avoid to some extent the screening effects of the tail plane and elevators at high angles of incidence. Under test all units produced recoveries from a standard flat spin except the normal tail unit and the first of the modified ones. The order of merit as deduced from the number of turns required to do so was F, E, D, B, C, A. It was noticed that the rate of turn of the steady spin was lower than that obtained with the standard tail unit for each of the modified units. Comparison of the results obtained with F and E, and D and B showed that the deepened fuselage was more effective than a wide one surmounted by a fin. The experiment as a whole clearly demonstrates the futility of providing a large rudder situated immediately behind and above the tail plane as a means of ensuring recovery from spins at high incidence; a relatively small rudder can produce rapid recoveries from a flat spin if the tail plane is raised to the top of the fin.

Effects of Altering Position of C.G. and Mass Distribution.—Tests on a Bristol Fighter model were carried out for three positions of the centre of gravity and for five conditions of mass distribution. This model also appeared to be able to spin in two distinct ways according to the initial motion in which it was launched, a slow steep spin at an incidence of about 35° with $\Omega s/V$ approximately .5 and a fast flat one at 60° and $\Omega s/V$ in the neighbourhood of 1.0.

A further difference between the two spins which is not without significance was that for the flat one the inner wing was found to be inclined at about 5° below the horizon, whereas in the other type it was about 2° above it; in other words, the rate of pitch was positive for flat spins and negative for steeper ones.

The moments of inertia of the model were measured by the oscillation method previously described and it was found that whereas A and C corresponded closely to the accepted full-scale values, B was about 20 per cent. too small.

It is thus not possible to compare the model spins directly with those of the aeroplane. The phenomenon of an aeroplane being capable of assuming two quite different spinning attitudes with the same control settings, although never definitely disproved, has never been consistently observed on the full-scale machine.

The model tests, however, seemed to indicate the stability of both types, over the limited number of turns for which they were observed; and in consequence, although it is not impossible that the slower spins were very gradually developing into the flatter type, no very serious error will result from assuming them both to be positions of stable equilibrium. The spinning characteristics of the model were deduced for three positions of the centre of gravity (corresponding to $h=0.33$, 0.4 and 0.5) of which the centre position represents a fully loaded machine.

It was found that the two types of spin were maintained for each C.G. position and that in each case the incidence increased as the C.G. was moved back. For the flatter spins $\Omega s/V$ increased with incidence whereas for the steeper type it reached a maximum in the neighbourhood of the normal C.G. position ($h=0.4$).

The characteristics of spins were next deduced for five conditions of mass distribution, the centre of gravity being maintained in the forward position and the total weight kept constant. Weights were added to the nose and tail to increase B by 40 per cent. and 70 per cent. and to the wing tips to increase A by 57 per cent. and 98 per cent.; the moment of inertia about the normal axis was of course simultaneously increased to the same extent in each case. The results of these changes were found to be insignificant as far as the steep spins were concerned.

On the other hand, the fast flat spin became faster and flatter as the quantity A-B was increased in the positive direction by adding weights on the wing tips. Loading the fuselage, making A-B negative and increasing C-A, was found to

lead to slower and steeper spins, but the changes were slow in taking effect and it was not possible to deduce the equilibrium conditions. This experiment has recently been confirmed on the full-scale aeroplane.

Future Model Work.—The experiments described above were brought to an end by the demolition of the balloon shed at the beginning of the present year. It was felt that although the method had shown itself capable of yielding valuable information of a general character, a further improvement in technique was necessary before it would be possible to obtain reliable quantitative data. The experiments were handicapped by the comparatively short length of the spins and by the difficulty of observing in detail the motion of a rapidly-falling model. These considerations led to the suggestion by Mr. McKinnon Wood that similar tests should be carried out in a large vertical wind tunnel, the descent of the model being neutralised by the upward velocity of the air stream. The practicability of this scheme has been demonstrated by means of a model vertical tunnel; it appears that models in general display a slight but definite lateral stability in that, if once truly launched in the centre of the tunnel, they will continue to spin almost indefinitely without coming into contact with the walls. The vertical position of the model in the tunnel can be controlled by varying the wind speed. The repulsion of the walls of the tunnel is, however, exceedingly small and is not expected to have any subsidiary effects upon the character of the spins. A vertical wind tunnel of sufficient size to accommodate models of two-foot span is at the present time nearing completion at the R.A.E. It is hoped that this apparatus will prove to be a ready means of accelerating the progress of the whole research. By reversing the controls (by means of a delayed action mechanism incorporated in the model), after a large number of turns of a spin have taken place, it should be possible to predict with all reasonable certainty whether a given aeroplane is capable of recovering from a prolonged spin, and many hazardous and inconclusive full-scale experiments will be avoided.

Full Scale Technique

Full-scale spinning experiments aim at determining the spinning motion of an aeroplane, either by means of recording instruments inside the machine or by the visual observations of the pilot or observer. In the last few years the use of recording instruments has very much increased. It has often been demonstrated that the impressions of even the most experienced pilot as to the altitude or rate of rotation of the aeroplane are apt to be unreliable in normal circumstances, and often totally incorrect in exceptional ones. It should, however, be mentioned that the routine spinning tests, which are now performed on every new type of machine, are accomplished without the use of recording instruments, and that since the institution of these tests, vicious spinning characteristics have only very occasionally been subsequently discovered on accepted types.

To determine completely the spinning motion of an aeroplane it is necessary to measure at least six independent quantities. Some choice of method is, of course, at the disposal of the experimenter, but the one which has been adopted in this country consists of measuring the components of angular velocity about the three axes of the aeroplane, the components of linear acceleration along these axes, and also the rate of vertical descent. Seven independent quantities are thus obtained, and one check on the accuracy of the observations is available.

Since the previous paper was presented to the Society no radical change has taken place in the methods of measuring these quantities, although the individual instruments have been improved from time to time. In their present form the instruments are still somewhat cumbersome, and it is not always practicable to fit them all to a small aeroplane. Fortunately it is not always essential to determine all the details of the motion: a fair approximation to the angle of incidence can be obtained from the records of an accelerometer placed at or near the centre

of gravity and the rate of turn about the vertical is easily determined. It has, however, been found impossible to measure the angle of sideslip in any direct way, and in consequence no analysis of the yawing and rolling couples is possible unless the complete determination of the motion is undertaken. There is no doubt that if a small and convenient instrument capable of measuring the necessary six quantities were available, the progress of research work on spinning would be very much accelerated. The development of various instruments for this purpose is being carried forward at the R.A.E.

Full-scale work on spinning is largely limited to measuring steady spinning conditions: for this purpose it has been found necessary to do spins of considerably greater length than was at first considered practicable. It is necessary not only to reach a steady state, but to remain in it for perhaps ten turns if the various quantities involved are to be determined with accuracy.

In practice the total length of the spin is generally about 25 turns, and the loss of height about 4,000ft.

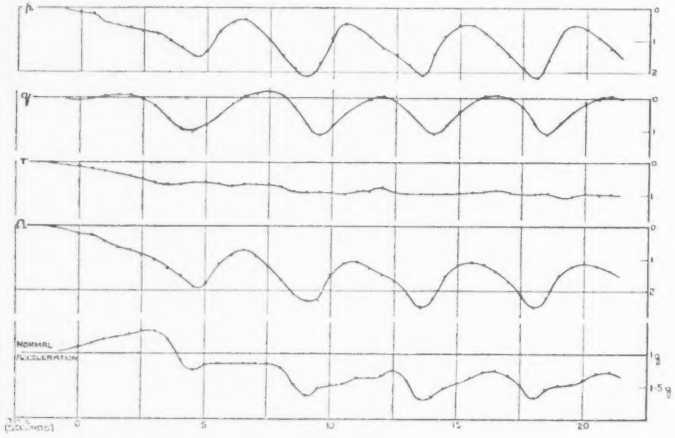


FIG. 28.

Records of a right hand spin.

It appears that spins of this duration do not in general have any incapacitating effects upon the pilot; moreover, he often becomes to some extent acclimatised to the motion after the first few turns and is able to take more comprehensive observations than would be possible in a shorter spin. In theory it is not possible to achieve a steady motion owing to the change in density of the air with altitude; no measurable discrepancy has been detected, however, between observed spins of the same aeroplane at various heights below 10,000ft. With most aeroplanes it is, in practice, possible to obtain records of what are apparently perfectly steady spins except for small irregular disturbances presumably due to atmospheric turbulence.

The theory of spinning is as yet largely based on the assumption of the steady spin, and it is difficult to deduce much from records which do not show a close approximation to this state: some aeroplanes have been found to have an oscillation in pitch, superimposed upon the steady motion which may, in certain circumstances, achieve a very considerable amplitude. The analysis of the equilibrium of an aeroplane in a motion such as this presents a somewhat difficult problem, and it is evident that some time must elapse before the causes of this

phenomenon are fully understood. Figure 28 shows a record taken in a spin on the aeroplane which we have designated as the typical landplane; it will be seen that the aeroplane alternately spins fast and steep and slow and flat. In this experiment a series of spins were done with different positions of the centre of gravity, and it was found that the amplitude of the oscillation increased as the C.G. was moved back, the mean value of the incidence being very little changed. It might appear from this that oscillations of large amplitude are indicative of factors tending towards the flat spin. Some importance is attached to this experiment, since it illustrates the existence of a type of spin which is at present largely beyond the scope of model experiments or theoretical investigation.

Full-scale experiments have lately been concerned with investigating the effects of various control movements on the character of the steady spin. It would be premature to discuss in detail the results of these experiments, but one or two general inferences are of interest. In the first place, it has been established that if the stick is moved forward during a spin, the rudder being held on meanwhile, a very much more rapid rate of spin is generally obtained: the incidence decreases as the stick is moved forwards, but often increases again as the rate of rotation rises until a final state is reached which may be flatter than the normal spin.

For one machine this effect was so marked that subsequent reversal of the rudder was insufficient to produce a recovery; the normal spin could, however, be regained by pulling the stick back again, and recovery was then immediately effected. It thus appears that misapplication of the elevators, such as might easily occur at the hands of an inexperienced or bewildered pilot, may lead to spinning conditions of a dangerous character on an aeroplane which can normally be regarded as perfectly safe. On the other hand, it has been found that reversal of the rudder while the stick is kept back invariably leads to slower and steeper spins, and often eventually produces a recovery.

The effects of various types of lateral control have also been investigated. Once the spin is developed the application of ailerons, whether normal, floating or differential, has in general had but little effect upon the motion, and there is no recorded case of any type having been sufficiently powerful to effect recovery against the rudder and elevators.

These experiments have, as already stated, been largely concerned with measuring the steady spinning motions obtained with various control settings. Future full-scale work will probably be more concerned with investigating more fully the immediate, as distinct from the final, consequences of certain control movements; it will be necessary to develop the technique of recording the spins so that a detailed analysis of unsteady motions, and particularly the motion of recovery, can be obtained.

Determination of Moments of Inertia

It is easily seen that an accurate knowledge of the moments of inertia of an aircraft is essential if an analysis of its spinning properties is being made. Since the inertia couples, which are largely responsible for the equilibrium of the spinning motion, are proportional to the differences of the moments of inertia about the three axes, it follows that small errors in the determination of the latter may result in much larger errors in the estimation of the former. In the past, reliance has been placed in the calculations obtained from a weight schedule; it has, however, been found that discrepancies of about 10 per cent. could arise, according to the particular approximation employed in the calculation. The only practicable alternative appeared to be to measure the moments of inertia directly by observation of the aeroplane's periods when swung as a compound pendulum about appropriate axes. This method has been greatly complicated by the discovery of the virtual mass effects previously referred to in connection with free flight

model work. It has, however, been successfully applied to the Bristol Fighter in this country. Similar experiments have been conducted on a number of aeroplanes in America, but there is no evidence that adequate virtual mass corrections were obtained.

The aeroplane was suspended by cables attached to its centre section, so that it could oscillate about axes parallel to the longitudinal and lateral axes; and a bi-filar suspension was used for swings about the normal axis. As it was not possible to conduct these tests in an atmosphere of low density, the magnitudes of the virtual mass corrections were deduced from model experiments. Two methods were employed:—In the first, a crude model of the aeroplane with rectangular wings and fuselage, whose moments of inertia could be calculated with accuracy, was timed while oscillating about the three axes, and the apparent moments of inertia deduced. As a check on the accuracy of this method, one of the free flight models—lightened as far as possible by the removal of the ballast weight—was swung in the R.A.E. altitude chamber at a pressure of one-fifth of an atmosphere, and also at normal pressure. For both model tests the suspensions employed corresponded precisely with those which had been used on the aeroplane. The corrections which had to be applied to the measured moments of the Bristol Fighter were 27 per cent. of A, 9 per cent. of B, and 3 per cent. of C.

It was further observed that the corrections did not vary in any simple way with the length of suspension employed, and also that the effects were largely due to details of wing section and shape, since no close agreement with the results derived from the crude model was obtained.

The main outcome of this work has been the demonstration that measurements of the moments of inertia by swinging tests are worthless without a subsidiary model experiment of some delicacy. Even when the whole experiment is conducted with the greatest care, the order of accuracy is only about 5 per cent., and it appears that, in general, reliance will have to be placed in calculated values of which the accuracy is perhaps 10 per cent.

Spinning Diagrams

We now come to the method of calculating what the characteristics of the spins of an aeroplane will be from model data. A convenient procedure was suggested to one of the present authors by Mr. Bryant. It may be briefly described as follows:—

(1) From the pitching moment incidence curves and the difference in the moments of inertia C-A the speed of rotation ps/V required for balance of pitching moments is found for a number of incidences from the formula

$$\overline{mi} = \{ (C-A)/\rho S s^3 \} \tfrac{1}{2} \sin 2\alpha \, (ps/V)^2.$$

(2) On the assumption that balance of forces and balance of rolling moments is required it is then possible to work out approximately from the expressions given below the sideslip (β) in the spin and also the yawing inertia couple.

$$\beta = - \{ \overline{lp} + \mu_L (b \sin \alpha) \, ps/V \} / \{ \overline{lv}/\beta + (b \sin \alpha) \, (ps/V)^2 \}$$

where $\mu_L = k_L/(w/g\rho s)$ and $b = (B-C)/\rho S s^3$

$$qs/V = (ps/V)\beta + \mu_L$$

$$\overline{ni} = \{ (A-B)/\rho S s^3 \} \cos \alpha \, (qs/V) \, (ps/V).$$

(3) The rolling and sideslip vector diagrams then give the aerodynamic yawing moments and it can be seen how much out-of-balance yawing moment there is.

(4) This out-of-balance yawing moment is plotted against incidence and on the figure are also plotted curves of this moment increased and decreased by the moment due to setting the rudder over on either side to its full extent. Wherever the x axis falls between the extreme curves it indicates that the rudder can provide enough moment to give balance in a spin.

If, as has so far been usual, the model data apply either to the straight flight condition, or to that of the simple rolling motion about the wind axis through the centre of gravity, the method outlined above only gives an approximation. The pitching moment curves are for instance affected both by the rolling motion and such yawing and pitching motions as there are in the spin. Data have, however, been obtained for most of these various effects on some particular model or other, and the curves of the spinning diagram may, if desired, be corrected for them, remembering always that such effects as are found from the simple model experiment may not apply exactly to the more complicated conditions of a spin.

One approximation usual in the curves, which may be mentioned here, is the neglect of both the aerodynamic and inertia couples due to the airscrew. These, in general, would not appear to have a large effect on the spin although in certain critical cases these couples may just turn the scale from safety to danger. Nevertheless, in spite of the approximations, which are admittedly many, and deserving of careful scrutiny in each case, it is gratifying that for the limited number of aeroplanes for which these diagrams have been drawn and for which quantitative full-scale data on spinning exist, the agreement is on the whole not bad. It will be seen, however, that when we come to consider the diagrams in relation to *rate of recovery* from a spin their interpretation is somewhat obscure. We consider this a point on which it is very important that theoretical work—probably lengthy and involved—should be carried out to elucidate the mechanism of recovery from a spin, and if possible, to reach a method by which rate of recovery can at all events be expressed roughly in terms of a few simple constants of the machine.

In what follows we shall consider the spinning characteristics of a few aeroplanes both as represented by their spinning diagrams and as they have been found in actual practice. The aircraft concerned are those seven previously mentioned, for which rolling vector diagrams have already been given. The moments of inertia used in the calculations are given in the following table:—

MOMENTS OF INERTIA USED IN OBTAINING SPINNING DIAGRAMS.

Value of ρ taken as 0.002, corresponding to approx. 5,000ft. altitude.

Aeroplane.	$A-B/\rho Ss^3$	$B-C/\rho Ss^3$	$C-A/\rho Ss^3$
Typical landplane ...	−0.235	−0.272	0.507
Typical seaplane ...	−0.261	−0.225	0.485
Original fighter ...	0.086	−0.386	0.30
Lengthened fighter ...	−0.241	−0.314	0.555
Deepened fighter ...	0.086	−0.386	0.30
Hornbill	−0.378	−0.283	0.660
" Bantam "	−0.097	−0.345	0.442

Typical Landplane.—Two sets of curves are given (Fig. 29). The upper set is for the elevators set hard up for spinning and the lower set for elevators hard down for coming out. The middle curve of the three is for rudder set at 0°, the upper for rudder with spin, and the lower for rudder against the spin.

The topmost curve for both rudder and elevators set for spinning indicates a spin at about 40° incidence and $ps/V=0.22$ to 0.23. The corresponding full-scale figures are approximately 43° and 0.3, but the curves show that no very large discrepancy between model and full-scale yawing or pitching moment is required to bring the results into rough agreement. Agreement in sideslip is not good; that indicated by the model curve is negligible, while the full-scale figure was of the order of 7° inwards (β positive).

The curves also indicate that if the elevators are set against the spin, a spin is still possible if the rudder is kept hard over for the spin; the incidence of the

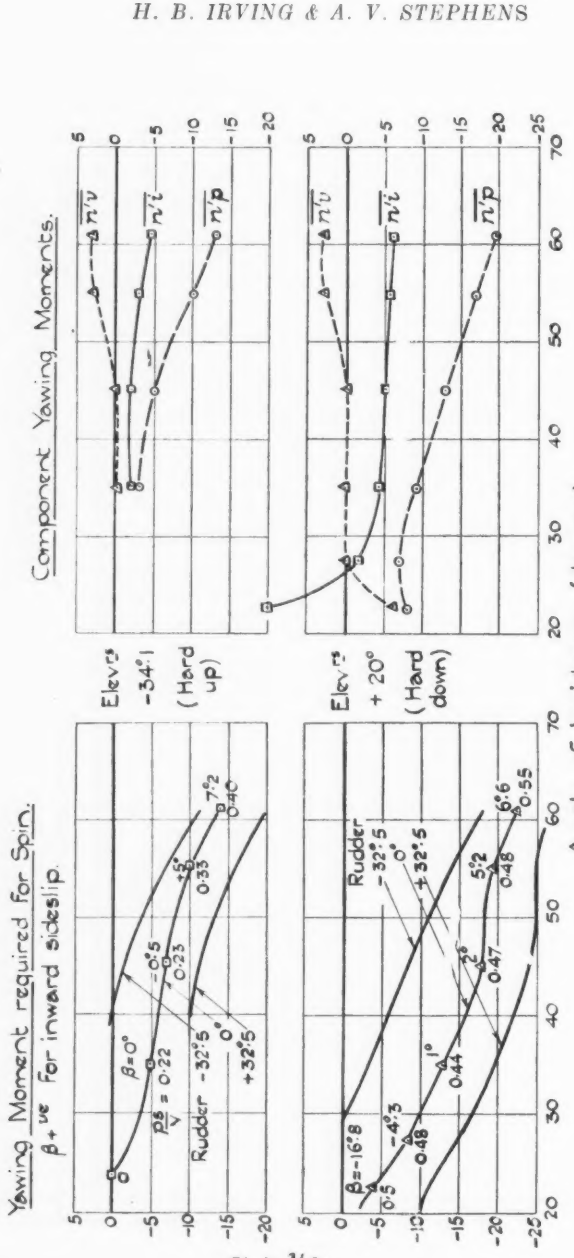


FIG. 29.

Spinning diagrams for typical landplane.

spin is, however, reduced, but the speed of the spin increases and the balance of pitching moments is preserved. But for any elevator setting a steady spin against the rudder does not appear to be possible; while for both rudder and elevators hard over against the spin there is, at all incidences, a margin of negative yawing moment which precludes the steady spin. The question as to the meaning of this margin in terms of rate or ease of recovery from an established spin is still rather obscure, because of the complicated process of recovery which, so far as can be seen, does not admit of simple treatment. A large amount of spinning has been done on this particular landplane, and recovery has generally been found to be quite easy and quick, but one case of difficulty has been met.

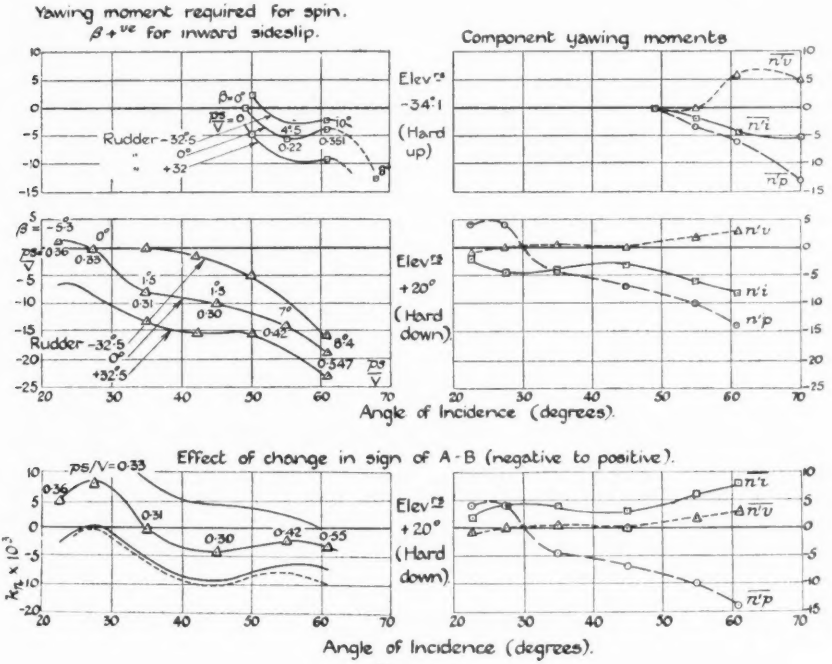


FIG. 30.

Spinning diagrams for typical seaplane.

In the last figure (Fig. 34) of spinning diagrams we have plotted together for comparison the curves for the different machines with controls set against the spin, and we discuss further the question of recovery after dealing separately with the diagrams for each machine.

Continuing with the landplane, some interest is attached to the curves for the separate components of yawing moment, $\overline{n'p}$, $\overline{n'i}$ and $\overline{n'v}$, plotted against incidence in Fig. 29 on the right. It is seen that $\overline{n'p}$ is chiefly responsible for the provision of negative yawing moment, $\overline{n'i}$ making some contribution, and $\overline{n'v}$ being mainly small and sometimes positive.

Typical Seaplane.—Reference has already been made to the fact that the floats of the seaplane were found to have a remarkably big effect on the pitching moment. We have seen that whereas, according to the model experiments with

the elevators hard up, the landplane trimmed at 23.5° incidence, the seaplane trimmed at an angle as high as about 49°. This means that, with elevators hard up, the seaplane can only spin at incidences greater than 49°, since as soon as rotation begins the incidence is increased by the pitching inertia couple. The diagram (Fig. 30) shows spinning with the rudder to be possible only over the small range of incidence from 49° to 52° at a low rate of rotation, which, as before, increases as the elevators are put down, to $ps/V = 0.31$ with elevators hard down. With both controls set against the spin there is still a margin of yawing moment adverse to the spin, but it shows some reduction as compared with the corresponding landplane. Reference to the curves giving the component yawing moments in the spin shows that this reduction is chiefly due to reduction in $\overline{n'p}$, which again is partly due to the moment due to the floats themselves, but is mainly accounted for indirectly by the reduction in ps/V brought about by the effect of the floats on the aerodynamic pitching moment.

As regards the full-scale behaviour of the seaplane in a spin, comparatively little is known. It did not spin fast, and at first its recovery seemed to be quite satisfactory. But on a later occasion the spin flattened after a few turns and hardly seemed to respond to the controls.

We have made this seaplane the subject of an example illustrating the effect of a change in yawing moment inertia. The value of A – B for the seaplane is negative and of quite appreciable value: if it were of equal value but opposite in sign the spinning diagram obtained for elevators set for coming out would be that given in the bottom part of Fig. 30 (full lines). We see that now, instead of having a fair margin of yawing moment for coming out, the curves suggest that the difference in inertias has brought the machine to a state in which it could take up a steady spin against rudder and elevators at an incidence round about 28°. The full line curves were arrived at on the assumption that the change of sign of A – B was unaccompanied by any other alteration, in which case $\overline{n'i}$ was merely reversed. If, however, we take the case which is approximately given by effecting the change in A – B by adding weights out on the wings, B – C is altered by as much as A – B (C – A remaining unaltered) and we get the result shown by the dotted curves. This indicates that alterations in B – C, although appreciable in their effect, are not of first importance.

Single-seater Fighters.—We now take the cases of the single-seater fighter and its two modifications. Here the dotted lines of the spinning diagrams (Fig. 31) apply to an altitude of about 15,000ft., and show the considerable effect which altitude may have. It is primarily due to the change in $\overline{n'p}$ which occurs as a result of the change in ps/V required to give balance of pitching moments when the density alters.

According to the curves for both altitudes of 15,000 and 5,000ft., the spin of the original fighter should not become steady till the incidence has exceeded 60°. The measured value was about 57°, but it seems to be quite possible that the spin had not quite reached a steady state even after the considerable number of turns (10) which were made. The speed of spin as indicated by the diagram varies from about 0.68 at 15,000ft., to 0.77 at 5,000ft. On the full scale it was estimated roughly as 0.77 and 0.71 in two spins to the right. There is here therefore, on the whole, fair agreement between model and full scale.

For controls set against the spin the diagrams again indicate that recovery should eventually be possible, but the full-scale report describes how great difficulty in recovery was experienced; the aeroplane did not come out of the spin till as many as 40 and 34 turns had been made in the two last spins. In the former spin, probably after about 30 turns, the pilot realised that he was applying rudder *for* the spin. Soon after this was remedied the aeroplane began to come out, which it did at about 7,000ft. In the next spin a rudder angle recorder was fitted. After reversing the controls, bursts of engine were tried with little effect, after which " the engine slowly stopped and as it did so the

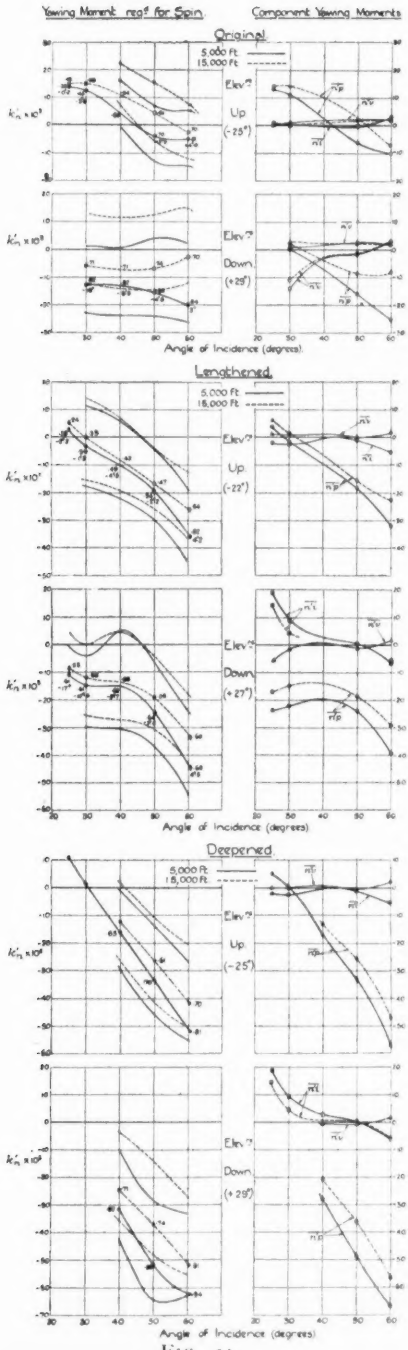


FIG. 31.

Spinning diagrams for single-seater fighter.

aeroplane slowly ceased spinning. Height after recovery 10,000ft." The rudder angle record showed a progressive decrease in rudder angle during recovery, not more than half the available angle being used during the later stages of the spin. " The pilot was partly aware of this, and states that it is very difficult to maintain full rudder for long in a spin if the force required is considerable, in the awkward position necessitated by application of full forward stick. The control record shows a final powerful application of full left rudder just before the recovery indicated by the change in the acceleration. It is probable that this assisted the recovery, although the pilot is strongly of opinion that the spin began to decrease in violence as soon as the airscrew began to slow down."

All this goes to show that a factor to be reckoned with in the question of non-recovery, or difficulty in recovery, from a spin, may be the failure on the part of even the most experienced pilot, under the influence of the confusing effect of the spin—and more especially a prolonged one—properly to execute the appropriate manœuvres for recovery. The fact that the aeroplane is also steadily losing height and coming into denser air on the other hand, has to be remembered in connection with those cases where in the last extremity the aeroplane has suddenly, and apparently unaccountably, come out of a spin.

Turning now to the fighter with lengthened body, it should be noticed that in addition to the lengthening of the body, the fin and rudder area were considerably increased and the tailplane raised from the middle to the top of the rear portion of the body. The wind tunnel experiments showed that these modifications gave greatly increased damping moments due to body, fin and rudder while rolling. Roughly as much of the increase was due to the lengthened and deepened body as to the enlarging of the fin and rudder. The result indicated by the spinning diagram is that the incidence of the spin should be reduced to about 46° at ps/V of about 0.53. These figures are both in good agreement with the full scale figures. The spins in the full scale experiments on this aeroplane had definitely settled down and were characterised as " exceptionally steady." Recovery was definitely slow, and three to four turns were required for recovery to an even keel. Previous full-scale experiments with a slightly smaller, and probably inferior, fin and rudder, had shown that the vices of the original fighter had not been entirely eliminated. The later form cannot, therefore, be regarded as having any great margin of safety so far as recovery is concerned.

The diagrams for the fighter with deepened body have been worked out on the assumptions that the aerodynamic pitching moment and the inertias are the same as for the original fighter. So far as pitching moment is concerned only a direct test would tell if the raising of the tailplane has much effect; but as regards inertias it would seem that in a new design there should be very little difference due to deepening. With the aeroplane which has been modified for full-scale experiments at Farnborough, however, the fuselage has been deepened by the addition of a light superstructure on which the raised tailplane is placed. This means some slight addition to $C-A$ and a change of $A-B$ in the negative direction. It has not been possible for the purpose of this paper to include the effect of these changes on the spin. The curves as stated represent the ideal case of deepening for which a new design of fuselage has been prepared, assuming pitching moments unaltered.

According to the diagrams with the controls set for spinning we now get a spin at about 40° incidence and $ps/V=0.63$. The actual aeroplane spins at 48° incidence and ps/V about 0.44. The fact that this latter figure is less than that given by the diagram for the lengthened fighter at the same incidence rather suggests that the pitching moments used in the calculations are in error and that this error together with the discrepancies in $A-B$ and $C-A$ should account for the differences between the calculated and observed results.

The curves for the deepened fighter with controls set against the spin show more margin of yawing moment adverse to spinning than those of any of the

aeroplanes previously considered. With the limited spinning experience on the actual aeroplane recovery has been found to be entirely satisfactory. With both rudder and elevator set against the spin recovery takes under two turns, while if the controls are centralised, the aeroplane will come out of a spin in three turns.

"*Hornbill.*"—The model data on which the diagram (Fig. 32) for the Hornbill is based, are rather meagre, the only information available being some tests on the rolling balance in connection with the unusually good stability and control of this machine at the stall. These were made on a model of body and wings only. Yawing moment (but not rolling moment) due to sideslip has been neglected, but the diagram indicates that below 50° incidence the sideslip does not rise above 5°, and in the spinning range is of such sign that if allowed

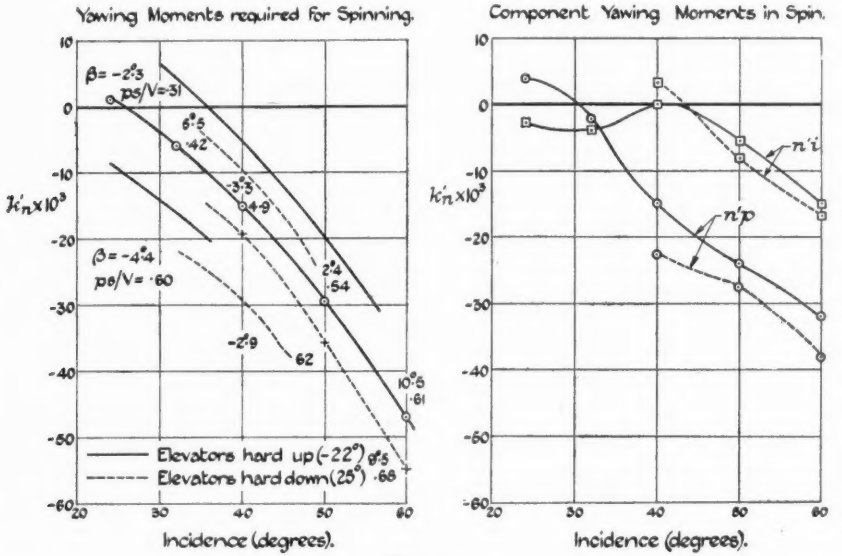


FIG. 32.

Spinning diagrams for Hawker "Hornbill."

for would in all probability mean a small numerical increase in the negative yawing moments. In view of the possibility of the complete ineffectiveness or even reversal of fin and rudder it has been thought best not to make any allowance for them with rudder straight. But to give some idea of the kind of spin possible with rudder set over a uniform value of the rudder control of 10 has been assumed.

As a result of even these somewhat rough calculations it seems a fairly safe conclusion that balance in anything approaching a flat spin is extremely unlikely, while, unless something unusual happens to the rudder and elevator control in the spin (which is unlikely if the incidence never increases to any very large value) there would appear to be an ample margin of moment adverse to spinning with controls reversed as compared with other machines. Speed of spin with the controls set for spinning we should expect to be at a ps/V of between 0.4 and 0.5. This is not at variance with the observed fact given by Major Bulman, of Messrs. Hawkers, that the spin of the actual aeroplane is

" not very fast." Besides knowing that the Hornbill recovers from a spin in " not more than three-quarters of a turn " (Major Bulman) this is unfortunately all the full-scale information we have on the spinning of this aeroplane.

From the curves giving the component yawing moments in the spin it will be seen that owing to the fact that A − B for the Hornbill is negative and of considerable magnitude, the inertia couple counts appreciably as a factor tending against the flat spin.

" Bantam."—Points at only two angles of incidence, 42.6° and 60°, are available for the Bantam curves (Fig. 33), for the rudder at 0° – or three if the angle of trim (speed of spin zero) is included. Rudder control was only measured at 60° incidence. The points serve, however, to give the general trend of the curves. With controls set for spinning equilibrium is obtained at about 46° incidence and ps/V round about 0.5. No definite full-scale figures are available,

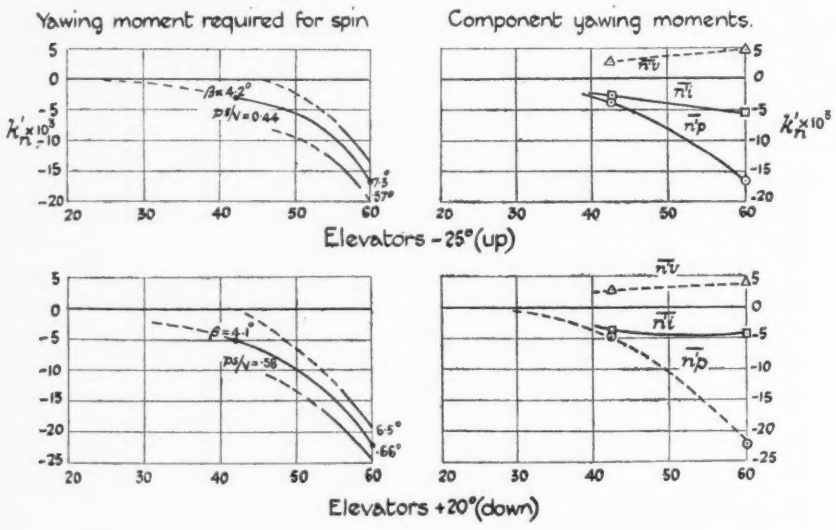


FIG. 33.
Spinning diagrams for " Bantam."

but we can say that these figures do not clash with the known fact that the Bantam spun fast and fairly flat. With controls set for recovery the margin of negative yawing moment is rather on the small side compared with that previously found. This aeroplane came fairly early among those which have given difficulty in recovery, but it has never been established that it could take up a steady spin against the controls. One fatal accident occurred before the type became obsolete, but in that accident the machine was flattening out while it hit a shed.

The Question of Recovery.—As previously stated we have in Fig. 34 collected together the various curves of the spinning diagrams which apply to the case of rudder and elevator set against the spin. We have done this in order to see whether the relative positions of the curves bear any relation to their known qualities of recovery on the full-scale aeroplane.

First we would comment on the fact that all the curves lie below the x axis. This means that for none of the machines is a steady spin against the controls possible; all should recover given time—and height—although recovery may

be slow, and any difficulty in recovery should generally become less as height is reduced.

But if we try to interpret the diagrams in terms of rate of recovery we find that the diagrams can only be regarded as rough indicators. It is true that the lowest curves, namely, those for the Hornbill and the fighter with deepened body represent aeroplanes in which recovery is definitely good. But the uppermost curves lie close together for two aeroplanes, one of which, the original fighter, is definitely dangerous, while the other, the seaplane, has only had doubt cast on its powers of safe recovery. In considering the indications of the

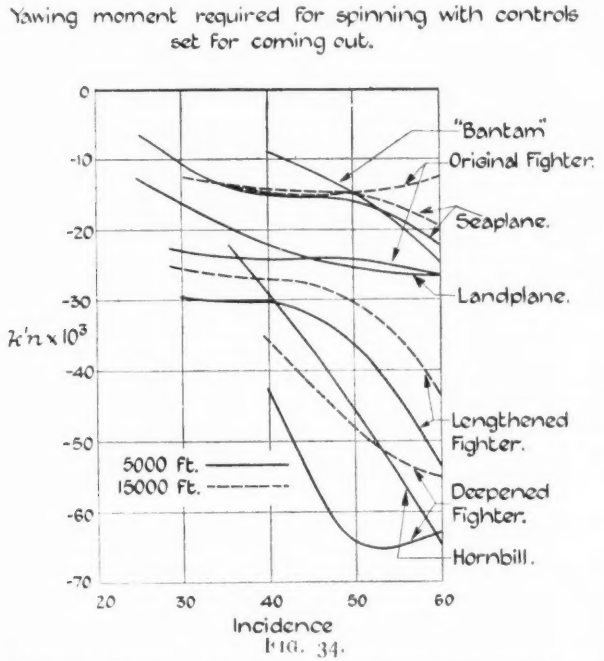


FIG. 34.

Spinning diagrams for various aeroplanes with rudder and elevators set hard over for recovery.

curves for these two machines it would appear that regard must be paid to the nature of the spins in each case. Both machines spin flat, but while the fighter spin is very fast, that of the seaplane is fairly slow. This difference in itself might account for all or most of the difference in recovery. For not only does the higher speed mean that a given damping couple takes longer to wipe out the spinning motion, but it makes the application of any damping couple through the rudder more difficult, besides, as has been seen, possibly confusing the pilot. Mr. Gates has calculated that in the spins of the original fighter the load on the rudder bar with rudder set fully over against the spin, due to centrifugal force, amounts to about 100lbs., one-third of this being due to the tail skid which is connected to the rudder.

According to the model rolling experiments on the original fighter the total rudder control to be obtained by reversing the rudder from $+33°$ to $-33°$ is a couple of nearly -20 about the axis of the spin. Such a couple acting by itself

would produce a deceleration in rate of spin of about 0.9 rad./sec.^{2} compared with a speed of spin of about 6.3 rad./sec., and the speed would be halved in about $3\frac{1}{4}$ turns. But there is also the effect of the elevator control to be considered. For when the elevators are put down we have seen that in the case of the Bantam they increased the shielding of fin and rudder and so produced a moment in the direction of the spin. Further, there is the sideslipping effect of elevator control, previously mentioned, which acts initially against the rudder control. In fact it would appear to be quite possible, as has been suggested by Bryant, that a quicker recovery might be obtained by some delay in moving over the elevators after the rudder has been set over.

If we refer to the rudder control of the seaplane we find that the model experiments show it to be on the poor side. The total at 60° incidence when rolling at a moderate rate is only about 6 about the axis of roll, which might be reduced to, say, 5 due to the elevators being moved over. This gives a deceleration of 0.2 rad./sec.^{2} due to the direct action of the rudder. If the speed of spin is, say, 3 rad./sec., we find that $3\frac{1}{2}$ turns are required to bring the speed down to half.

The above remarks serve to show that we have not yet reached a satisfactory position so far as interpretation of the spinning diagrams in terms of rate of recovery is concerned. The diagrams generally seem to give spins for controls set with the spin which are not greatly at variance with the full scale, although the number of cases on which judgment can be based is small. Whether the diagrams are in error, or are actually consistent with the observed reluctance in recovery in certain cases cannot be determined without further theoretical work on the complicated mechanism of recovery. In the meantime, however, the wisest course appears to be to ensure easy recovery first by the provision of sufficient fin and rudder area so placed that it does not lose effectiveness in the spin, second by the provision of a rudder control which also does not lose effectiveness in the spin. The former will ensure that it is not possible for the flat spin to develop, which in turn makes easier the task of the controls (and generally also of the pilot in exercising these controls) in returning the machine to an even keel.

The Effects of Stagger and Wing Section in Relation to Inertia

It has generally been held that positive or forward stagger is beneficial as regards safety in spinning. The chief grounds for this belief are briefly that (*a*) stagger increases the retrograde movement of the centre of pressure beyond the stall, thus giving rise to increased stability in pitch, and (*b*) stagger in general reduces the tendency to auto-rotation at high angles of incidence.

As the result of the insight into the balance of forces and moments which the carrying out of spinning calculations on a number of aircraft has given us, we have come to the conclusion that any general conclusion as to the beneficial effect of stagger is unsafe. It would be difficult to give in a few words all the reasons on which we base our belief; but we shall try here to present briefly the line of argument, and to show that the question is intimately bound up with that of the sign of the yawing inertia moment which depends on the difference, A – B, between the moments of inertia about the longitudinal and transverse axes. This difference is sometimes positive when it is usually small, but is more often negative when it may be big.

Let us start by considering the rolling vector diagrams for two R.A.F.15 biplanes of equal chord and span and gap=chord, with 0° and 30° stagger (Fig. 5). The most marked difference which strikes one in the two sets of curves is that, generally speaking, those for 30° stagger are displaced to the left compared with those for 0° stagger. That is, stagger gives the more stable rolling moments. This means, that for balance of rolling moments in a spin in general stagger leads to outward sideslip, and absence of stagger to inward sideslip.

If, next, we examine the values of the yawing moments in the two cases we see that sometimes, at given incidence and ps/V, one set of curves has the more positive or negative value, sometimes the other. But it is easy to pick out a case in which stagger gives the greater positive yawing moment. In doing this some allowance should be made for the fact that since stagger increases longitudinal stability the speed of spin to give balance of pitching moments at the same incidence would be greater for the case with stagger; for instance, a ps/V of 0.5 for zero stagger would generally become about 0.6 for 30° stagger. At 50° incidence and $ps/V=0.5$ the yawing moment (chord axes) for zero stagger is nearly zero; at $ps/V=0.6$ for 30° stagger it is over +7. These values are for wings only; if we consider a complete machine the increased negative yawing moment given by body, fin and rudder at the higher speed of rotation might easily wipe out this difference. We see then that as regards yawing moment due to rolling a case might arise in which stagger has no effect.

Next consider yawing moment due to sideslip for the same cases as before. We are not on very sure ground here, but as far as our data go we can say that it is possible to have a machine in which the inward sideslip for the case of zero stagger would lead to negative $n'v$ while the outward sideslip for 30° stagger would lead to positive $n'v$.

Now consider the question of the yawing inertia moment. It is seen from the formula

$$\overline{n'i}=\{(A-B)/(\rho Ss^3)\}\cos\alpha\,(qs/V)\,(ps/V)$$

that its sign depends upon the sign of A − B and the sign of the rate of pitch q. The sign of q depends on the sideslip β for we have

$$qs/V=(ps/V)\,\beta+\mu_L \text{ where } \mu_L=k_L/(w/g\rho s).$$

The expression μ_L is essentially positive so that q is always positive when β is positive, which always occurs when $\overline{l'p}$ has any appreciable positive value.

It is thus seen that, if we assume A − B to be negative the positive values of $\overline{l'p}$ given by the case of zero stagger lead to negative values of $\overline{n'i}$ while the negative values of $\overline{l'p}$ given by 30° stagger lead to $\overline{n'i}$ being either less negative or possibly positive.

We can conclude then that a case might easily arise in which balance of forces and moments in a faster spin at higher incidence would be facilitated by stagger, and this would appear to be more likely if A − B is negative. But if A − B is positive we think that stagger will in all probability be advantageous.

It would be better, perhaps, if we put the above conclusion rather more generally. In the vector diagrams we have given for the purpose of illustration the case of 30° stagger gives us mainly negative $\overline{l'p}$, but as has been seen (Fig. 8) it is possible to have a staggered biplane which gives big positive $\overline{l'p}$ at high angles of incidence. Whether this is due to wing section or to the relative sizes of the unequal wings is uncertain, but it seems better to leave the question of stagger out and to say that where the properties of the wings are such as to give large positive values of $l'p$ over the spinning range, to have A − B positive is definitely bad. On the other hand, where $\overline{l'p}$ is negative the sign or magnitude of A − B may matter little. This happens because in the region $\overline{l'p}=-10$ to -20 the rate of pitch becomes zero and with it $\overline{n'i}$ vanishes regardless of the value of A − B, so that when $\overline{l'p}$ is negative $\overline{n'i}$ is usually smaller than when $\overline{l'p}$ is positive.

In considering previously the spinning diagrams for the typical seaplane with sign of A − B changed (Fig. 30), we saw an actual example of the adverse effect of positive A − B when there was no stagger and $\overline{l'p}$ was mainly positive (see Fig. 10).

Further, in the model dropping experiments which have been described it was seen that while the spin was steep alteration of A − B had little effect on the

spin, whereas when it was fast and flat alteration of A – B made it faster and flatter. These experiments were made on a Bristol Fighter with wings of R.A.F. 15 section (for practical purposes) the stagger being 17·5°. From our knowledge of the results on the R.A.F. 15 biplanes with different staggers we should expect that at the incidence of the steep spins, which was about 35°, $\overline{l'p}$ would be negative; but that for the fast flat spins at 60° incidence there is not enough stagger to prevent $\overline{l'p}$ from becoming positive. This expectation is borne out by the results.

There are also some interesting full-scale experiments bearing on the foregoing which were carried out in America and have been described by H. A. Sutton. The effect on spinning of adding weights well out on the lateral axis (thus increasing A – B) was tried on two biplanes both of which initially gave no trouble in recovery. On the one machine the addition of the weights caused difficulty to occur, while on the other they caused no difficulty in recovery and had only a small effect on the spin. In the former machine there was no stagger, while the latter was a sesquiplane in which there was some stagger combined with some sweepback on the upper wing (see Fig. 35); the leading edge of the tailplane was also swept back about 30°.

We have therefore one case on the full-scale in which $\overline{l'p}$ was almost certainly largely positive due to absence of stagger, and in which alteration of A – B in the positive direction was found to lead to difficulty in recovery; and another case in which $\overline{l'p}$ was probably mostly negative, in which alteration of A – B was found to have little effect on the spin. In fact we would go as far as to say that in the latter case we know $\overline{l'p}$ was negative *because* variation in A – B had little effect on the spin.

Further evidence on this point is furnished by a recent experiment at Farnborough in which the spins of a Bristol Fighter were measured with a series of weights incorporated in the wing tips. It was found that both incidence and $\Omega s/V$ increased with the size of the weights until values of 65° and 1.0 respectively were obtained with a 75 per cent. increase in A. Recovery from these spins became progressively more difficult. From the records it is clear that the value of $\overline{l'p}$ must be positive and further that it increases with α and $\Omega s/V$ up to the highest values obtained. In this case the angle of stagger is 17° and it appears that in general large positive values of A – B should be regarded as dangerous unless the stagger is exceptionally large.

We now see that even when stagger can be relied upon to reduce the autorotative tendency in a biplane it is only certain to be advantageous when A – B is positive. Similarly positive A – B is definitely bad only when there is no stagger or when, even with stagger, positive values of $\overline{l'p}$ occur under spinning conditions.

It is a corollary on the foregoing that, since changes in stagger cause differences in rolling properties similar to those caused by changes in wing section, what we have hitherto regarded as " bad " wing sections from the spinning point of view are not necessarily bad. For we have seen that in the " bad " wing with its positive values of $\overline{l'p}$ some inward sideslip is required to give balance of rolling couples, and that if A – B is negative this turns to advantage in that it leads to a negative yawing inertia couple. We should add the proviso, however, that the scale may be turned against any advantage the " bad " wing may have in this respect if its values of $\overline{n'p}$ compare unfavourably with the wing giving negative $\overline{l'p}$, as may occur with thick wings.

A further point which would appear to emerge from our reasoning is that one cannot generalise as to any superiority of monoplane over biplane as regards spinning, or vice-versa. The advantage may lie on either side according to the

aerodynamic qualities of the particular section or arrangement in relation to the moments of inertia of the design.

We realise that reasoning and conclusions such as the above are not very satisfactory from the designer's point of view. But they do at least throw light on the mechanism by which changes in wing arrangement, wing section, and inertia affect the spin. The rolling vector diagrams for wings and complete aeroplanes which have already been determined should give some sort of idea as to the kind of diagram to be expected in any particular case, although it must be admitted that our data are by no means sufficiently comprehensive to preclude a considerable degree of uncertainty in some cases. We would remark that, as far as we know, in no other country than England have rolling vector diagrams

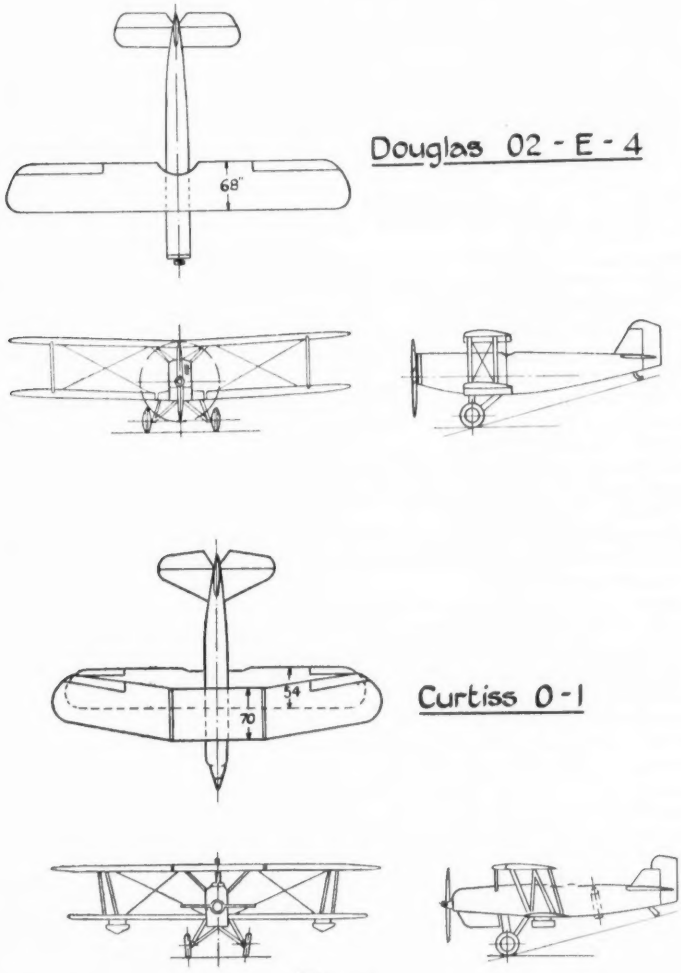


FIG. 35.

American aeroplanes tested for inertia effects on spinning.

been determined either for wings or complete models: if other countries also obtained diagrams, which were published, we should all the sooner build up a comprehensive body of data to the general advantage.

Conclusions

Any general conclusion that stagger conduces towards safety in spinning is unreliable: the effect of stagger depends in general on the moments of inertia of the aeroplane.

When A – B is positive we may generally expect stagger to be beneficial.

When A – B is negative it is possible for stagger to be disadvantageous.

With wings which give positive (unstable) values of rolling moment due to rolling ($\overline{l'p}$) under spinning conditions it is definitely bad to have A – B positive; in other words, the addition of weights on the wings may make such a machine dangerous in spinning.

With wings which give negative values of $\overline{l'p}$ in spinning the sign or magnitude of A – B is probably generally of little importance, and the addition of weights on the wings will have little effect on the spin.

By using " strip " theory a fair approximation to the rolling moment due to combined rolling and sideslip can be obtained from data on rolling and sideslip acting separately.

The rudder is by far the most effective control for the purpose of recovery from an established spin.

Ailerons are not likely to effect recovery by virtue of the rolling couple they can produce: their influence in stopping or augmenting the spin will be governed rather by the yawing moment which they exert (body axis).

Powerful elevators will probably, in general, effect recovery from a spin; but the initial effect of setting elevators against the spin will always be to tend to set up another and faster spin.

It is not clear that reversal of elevators invariably assists recovery during the flat spin stage, and some delay in moving the elevators down may conceivably help in certain circumstances.

The following are beneficial both as tending to prevent the development of the flat spin and the falling off in rudder power while spinning:—

Raising the tailplane.

Sweeping back the tailplane or moving it aft of the fin and rudder.

Positive dihedral angle on tailplane (bent upwards).

Deepening the body.

Seaplane floats generally tend in their effects towards making the spin flatter and slower. Their chief effect is on pitching moment, producing a large positive moment and reducing the elevator control in the spin. They also produce some positive yawing moment at flat spinning angles and seem to reduce rudder control.

Differential ailerons, while probably of some use in recovery if the spin does not become flat, are apparently of little use in a really flat spin.

Floating ailerons may be expected to effect but little improvement as regards recovery from a spin.

Spinning calculations, based chiefly on rolling balance tests of a complete model rotated about the wind axis through the centre of gravity and a knowledge of the moments of inertia, appear to give a fair approximation to the spinning characteristics of the aeroplane and a rough indication as to its quality of recovery.

Finally, we should like to add that we are indebted to the Aeronautical Research Committee and to the Director of Scientific Research, Air Ministry, for permission to make reference in our paper to certain recent experiments, the results of which have not yet been published. We are further indebted to Mr. Wimperis for the loan of the model vertical tunnel for demonstration purposes, and for the films you have seen, this evening.

Note added later.—Since the reading of the lecture our attention has been drawn to the fact that we omitted to pay any direct tribute to the work of the late Mr. K. V. Wright. We would hasten to repair the omission to the best of our ability. Mr. Wright was responsible for the research work on spinning at Farnborough for more than three years and the progress which we have described is largely due to his industry, ingenuity and patience. He developed the method of measuring spins, which has been the basis of all subsequent full-scale work and also the technique of the free flight model experiments. We can only hope that the ultimate solution of the problem of spinning will be a worthy memorial to one who worked so wholeheartedly in the cause of aviation.

References

Arranged in chronological order.

The spinning of aeroplanes. Gates and Bryant. October, 1926. R. and M. 1001.

Further experiments on a model of the "Bantam" aeroplane with special reference to the "flat" spin. Irving and Batson. June, 1927. R. and M. 1107.

The spinning of aeroplanes. Bryant and Gates. Roy. Aero. Soc. Journal, July, 1927.

Airplane spinning characteristics. H. A. Sutton. February 15, 1928. Air Corps Information Circular No. 613.

Experiments on a model of a single-seater fighter aeroplane in connection with spinning. Irving and Batson. May, 1928. R. and M. 1184.

Pressure distribution over a yawed aerofoil. Williams. October, 1928. R. and M. 1203.

Rolling and sideslip experiments on a model slotted biplane of R.A.F.31 section. Irving, Batson and Maidens. February, 1929. R. and M. 1240.

Experiments on the spinning of a Bristol Fighter aeroplane. K. V. Wright. May, 1929. R. and M. 1261.

Spinning experiments on a single-seater fighter. August, 1929. Part I.—Further model experiments. Batson and Irving. Part II.—Full scale spinning tests. Gates.

Spinning of a model of the Fairy III.F seaplane. Irving and Batson. June, 1930. R. and M. 1356.

Note on recovery from a spin. Bryant and Miss Jones. October, 1930. R. and M.

The determination of the moments of inertia of aeroplanes. Gates. March, 1931. R. and M. 1415.

Free flight spinning experiments with single-seater aircraft H and Bristol Fighter models. Stephens. April, 1931. R. and M. 1404.

Measured spins on aeroplane H. Gates. April, 1931. R. and M. 1403.

The effect of centrifugal force on the controls in a spin. Gates. May, 1931. R. and M. 1416.

Note on the addition of rolling moments due to roll and sideslip. Irving. June, 1931. R. and M.

Rolling experiments on a model of the Hawker "Hornbill" wings and body. Irving and Batson. July, 1931. R. and M. 1422.

Spinning experiments on a single-seater fighter model with deepened body. Part I. Model experiments. Irving and Batson. Part II. Full-scale tests. A. V. Stephens. December, 1931. R. & M. 1421.

Discussion

The Chairman: The first question to be settled was whether spinning was necessary at all. Responsible opinion was that they did not want to spin, and that if one could design aeroplanes, without interfering with other qualities, so that they could not be made to spin at all it would be a good thing. Inasmuch as present-day aeroplanes are capable of spinning, however, they had next to consider the question how far it was necessary to study intentional spins, bearing in mind that aeroplanes were fitted with instruments such as turn indicators which should enable pilots to avoid spin. The answer to that was that even the best of instruments might sometimes fail, and further, that occasionally a pilot might lose consciousness temporarily and his machine might get into a sustained spin before he recovered. It was absolutely necessary, therefore, that spin should be studied. There were several ways of studying it, and the lecturers had dealt with the mathematical method as well as the experimental use of models. The models used in the wind tunnels might be either free or constrained. For some time he had envisaged a vertical tunnel in which would be a rising current of air as especially applicable to certain experimental work in which it was necessary to observe the behaviour of falling objects; and although the first vertical

tunnel for model work was built in America, it was not the kind he wanted as the air stream was downwards instead of upwards. The reason for adopting a vertical axis for this American tunnel was to study the forces acting upon the spinning models during rotation. If, as in the older tunnels, the rotation were about a horizontal axis with gravity acting at right angles, there was lack of symmetry. In a vertical tunnel there was symmetry; but it was far better to go to the trouble of putting the airscrew at the top and to have the air flow vertically upwards, because then the model could be left unchained. It had appeared at first that the outer wing tip of a spinning model in the tunnel would tend to seek the wall, since the rotary motion would be retarded at the wing tip. The model might then dash against the wall. It was found, however, that the models did keep away from the walls. This was fortunate, but the reason was not obvious, but no doubt Mr. Irving could explain it.

One of the prettiest experiments referred to in the paper was that in which models were tested in a hydrogen tank. The idea of putting a small model of an aeroplane into an atmosphere of hydrogen for testing seemed odd at first, but it provided a means of swinging a model in order to measure the moments of inertia without a relatively heavy atmosphere having to be moved with it, thus avoiding having to make a rather uncertain correction for virtual moment of inertia.

The experimental work on models in the balloon shed at Farnborough had had to be discontinued for a very good reason; the shed was being pulled down. The Cardington sheds were still available, but best of all the new 12ft. vertical tunnel was expected to be ready at Farnborough in December of this year.

Some of the factors in spinning which had seemed simple had been found to be more complicated as the work proceeded. At one time it had seemed that in the moment of inertia problem, the C – A provided a kind of special factor in spinning, and that once a certain angle of incidence was exceeded one could not get back to level flight until one had got over a hump in the curve of gyrostatic effect. But it was found that C – A did not suffice for our needs; they had to take into account A – B; and it was not as easy as A, B, C!

It appeared that the outcome of the work, so far as it had proceeded, was that the trouble arose in the position of the tailplane, and they were beginning to know how to deal with that. The tail was the villain of the piece, and if it were not treated in the right way there was likely to be dangerous spinning. Indeed, if one had to summarise the advice of the research workers in two words, the nearest that one could get would be " tails up."

Captain F. S. Barnwell (Bristol Aeroplane Company): The subject of spinning was one of extreme complexity. He welcomed the paper as one of very great value to designers, because it would assist them to clarify their ideas as to the causes and the prevention of spinning. He drew attention to the statement at the beginning of the paper to the effect that although a particular aeroplane might be very unwilling usually to go into a spin, there was no guarantee that it might not do so under some unusual circumstances as, for instance, when flying in clouds; he asked what it was that a pilot was likely to do when flying in a cloud that he could not do, although trying to, when outside a cloud. With regard to the statement that some machines which were very unwilling to spin, were " vicious " when they did spin, he asked whether that characteristic was associated with unusually large moments of inertia. Another statement in respect of which he asked for some elucidation was to the effect that " a sideslip of 10° (without rolling) would give rise to a rolling moment large enough to balance the biggest unstable rolling moment ever found, in tests without sideslip, on the rolling balance." He gathered that the expression " unstable rolling moment " meant rolling moment *due to rolling;* because obviously there could be no " static " rolling moment if there were no yaw. But was not that a comparison

of a " static " moment with a moment due to rotation, which seems open to danger?

The result of the investigations described in the paper appeared to be that the rudder was the organ of greatest value for recovering from a spin, and he asked if any mathematical research work had been done on the " tail-first " or the " tail-less " aeroplane. It appeared probable that the heavy sweep-back of the normal " tail-less " aeroplane might have considerable value from the anti-spin point of view; but, judging from some little work he had attempted in regard to stability—not spinning—he did not believe that a " tail-first " machine could be made laterally stable at all unless one added vertical surface aft of the C.G.; this means having a " tail " back and front, which might be considered a definite disadvantage.

Only twice had he fallen into a spin inadvertently. On the first occasion he was anxiously studying the ground, to choose a place on which to land, he had allowed the machine to drop a wing and it had commenced to spin. He got out of it on that occasion by at once giving " full engine "; that, of course, made a big increase in the " power " of the rudder. The second occasion was when he attempted to " flick-roll " an aeroplane which he was flying for the first time. His impression was that giving full " opposite " rudder did not check the spin appreciably, but giving " top " elevator did stop it.

To him, as a designer, the brightest sentence in the paper was that which indicated the possibility of making machines safe without any radical alterations. Designers had to design aeroplanes which were to be constructed and flown, which would give the best possible performance and have pleasant stability and control characteristics; to these ends the " engineering " aspects were well nigh as important as the " aerodynamic." Some of the devices referred to in the paper as being good from the " anti-spin " point of view were not good from the point of view of " engineering design," as they would obviously entail greater weight and complication than in a " normal " lay-out. They probably suffered from spinning troubles since the war because there had been a tendency during the war to make machines with short-tailed bodies and small tail surfaces. Obviously, the reason for doing this was that the weight and drag of the body and tail were reduced, whilst rapid response to controls and light controls (without having to balance them) were thereby achieved.

Naturally, the designer was anxious to do all he could to render an aeroplane safe to fly, but he had to recognise the disadvantages of any increases of weight, drag or complication which were considered necessary to achieve such safety. Loss of efficiency in doing its normal job, in order to achieve safety when an aeroplane is doing abnormal things, necessarily somewhat perturbs the designer. He apologised for labouring a point not only obvious but somewhat irrelevant.

He concluded by thanking the authors for their extremely interesting and valuable paper; thorough investigation of this nature is of primary importance in achieving requisite safety in the most efficient way.

Captain G. T. R. HILL (Westland Aircraft Company): He gathered that the virtual mass effect arose primarily because a certain weight of air became entrapped with the wing and moved with the wing. One could get quite a fair physical idea of that effect, but he asked if the effect operated in a steady spin, because in all calculations they took into account the moments of inertia, C – A, and so on, but, so far as he could see, they neglected the virtual mass effect in this particular case; he could not understand why they could neglect the virtual mass effect in the case of a steady spin, whereas it had to be taken into account in correcting a measured moment of inertia obtained by swinging an aeroplane or a model.

Commenting on the point that, in the matter of spin, the tail and rudder system as a whole was really the villain of the piece, he said he felt sure he would

be excused for suggesting that difficulties due to the tail could be avoided in a simple way by cutting off the tail altogether; some people, of whom he was one, were very hopeful that that would prove ultimately to be the right way to achieve complete immunity from spin, but he was afraid that the results of the work that was being conducted in that connection would not be available for a while.

He had always taken a great interest in work concerning spinning, and he had experienced his first spin in the year 1916. Anyone who had got into a spin at that time and had managed to get out of it safely was regarded as having enjoyed more than his fair share of luck; nowadays, however, the work carried out both with models and with full-scale machines provided a very large additional measure of safety when spinning tests were contemplated on any new type of machine, and the work of Mr. Irving and Mr. Stephens, and their collaborators, was such as to place the researches of this country well in the forefront of all researches of this kind throughout the world.

Mr. L. W. Bryant (National Physical Laboratory): It was particularly gratifying to learn that a little of the later theoretical work had produced results which agreed with results obtained in practice. At any rate, they had obtained a great deal more data on which to base sound theories. Mr. S. B. Gates and himself, in their original paper, had been able to show that the attitude of an aeroplane in a spin was prescribed within narrow limits by the requirements for the balance of forces. A useful conception for visualising attitude in a spin at a given incidence was to think of the normal to the wing chord making an angle with the vertical equal to the incidence, the wings being horizontal, and then to imagine the aeroplane rotated through a small angle in either direction about that normal as an axis. This would give a close approximation to attitude at the given incidence. They had shown also that a small angular displacement of position such as this led to large differences in rolling moments about the body axis, and that a balance of these moments could always be found for any attitude. Since, also, balance of pitching moments depended almost entirely on rate of spin and on $C-A$, they had deduced that a spin at any incidence was possible unless a yawing moment was forthcoming to stop it. As they were not able to estimate yawing couples, they had had to leave it at that. Mr. Irving's discovery of the blanking of the fin and rudder by the tailplane had shed the first streak of daylight on to the mystery of the flat spin, and now his emphasis on the $A-B$ couple promised to explain many anomalies still outstanding. Mr. Stephens' confirmatory experiments on the full scale and with dropping models did him very great credit.

Seeing that yawing moments were all-important in determining equilibrium, in making the spin possible, it seemed only logical to pay special attention to them when looking for factors producing recovery. They could either provide an opposite rudder direct or move the other controls so that the motion tended towards a spin where the yawing couple balance was more difficult to get. He believed that sometimes, for steep spins, both these operations could be performed. But in the flatter spins the second alternative was not practicable. A pure rolling couple against the direction of spin led to a new spin, not appreciably different from the old. Rate of spin and incidence were hardly affected; there was simply a small change of sideslip and rate of pitch. A pure pitching couple in the direction of elevators down had a similar effect, only here there was always a tendency to speed up the spin, the incidence change being slight. They were thrown back, therefore, to the direct rudder moment, which, if large enough, was always immediately effective. A combination of the controls must always initially reduce the rudder effect, so that delay in applying elevators was always advisable in flat spins until the rudder effect had had time to show itself. Opposite ailerons were often effective on account of the assistance they gave the rudder.

The authors of the paper had done good work in emphasising the importance of yawing moment balance, showing that all questions of stagger, C.G. position,

C – A, wing loading, air density, etc., could be settled only by their effects on aerodynamic yawing moments and by their effects on the A – B inertia couple. In connection with the A – B couple it was noteworthy that modern machines seemed to tend towards a big negative A – B on account of the loading up of the body without at the same time spreading loads on the wings. A monoplane was an extreme example of this effect, and quite possibly petrol tanks or other loads on the wings would be a marked advantage in steep spins where fin surface might not be effective.

Mr. H. L. STEVENS (Martlesham): With reference to the authors' statement that in no recorded case had a spin been stopped by ailerons against the elevator and rudder, he said he did not think that that was strictly correct—though the two recorded cases he could remember related to an "Avro," and therefore, perhaps the spins would not be called real spins. However, he seemed to remember that an "Avro" with differential ailerons was brought out of a spin with ailerons alone against the rudder and elevator, and also with the first slot and aileron control. He also quarrelled with the suggestion that full-scale experiments were inconclusive, for he thought one could hardly call an experiment inconclusive when the aeroplane ended in a heap on the ground and the pilot sailed down to earth on a parachute. Commenting upon what had been referred to as the "tails up" method, he said that that might possibly lead to difficulties if an aircraft were to spin upside down, as it probably would do as soon as it was cured of spinning the right way up. The thing to do with enemies was to "twist their tails," and he suggested that if the tail were twisted through 45° and elevators and rudder interconnected it was probable that an aircraft machine would result which would not spin. The object of experiments in the spinning of aeroplanes was to endeavour to ensure that in service the aeroplanes would not be dangerous, but he was not quite convinced that prolonged spin tests were necessary, because he did not think one was likely to get an aeroplane into a long spin by accident, even when fighting. Prolonged spin tests were made in order to be sure of getting the aircraft into the worst spin that was likely to occur even by accident, and the 8 or 10-turn experimental spins might be unnecessarily long.

Mr. NAYLOR: With reference to the authors' statement that some aeroplanes were unwilling to spin, but that when they did spin it was difficult to get them out of it, he personally regarded spinning as a natural thing for an aeroplane to do. Elementary mathematics lead to the conclusion that an aeroplane should go into a spin normally and come out of a spin normally. If, by reason of some peculiarity, it would not go into a spin, or if it did not spin evenly when it did spin, or something of that kind, then perhaps at some time it might be dangerous, and he asked if there were any connection between irregularity of spin and difficulty of recovery.

He said he had believed hitherto that a backward position of the centre of gravity had a bad effect on spinning, and yet he had heard of two cases in which it was more difficult to recover from a spin when the C.G. was forward than when it was further back; he asked if Mr. Irving could explain this apparently anomalous result.

Commenting on the references that had been made to horns and tails, Mr. Naylor suggested that the horns had a little to do with it as well as the tail. They had been told that there was a balancing yawing moment, and also that the effect of the ailerons in a spin was important, not because of the rolling moment, but because of the yawing moment. He suggested that perhaps if they could put on a yawing moment in some other way during a spin, by putting on some sort of horns, or a parachute, or something of that kind, then recovery from the spin might be accelerated at will.

Dr. LACHMANN (Messrs. Handley Page, Ltd.): With reference to Bryant's conclusion on the effect of the rate of roll applied to the spinning motion, which

would produce a sideslip, and which would in turn tend to keep up the rate of roll, he enquired whether this conclusion would also cover the case of a wing where by some means the auto-rotative characteristics were entirely destroyed. Would not this result in the complete damping out of the auto-rotative motion?

Discussing some experiments he had made with wing slots and interceptors, he said that he had had more promising results with them than Mr. Irving had had with interceptors only. These results had been confirmed partly by full-scale trials with a Bristol Fighter and a Moth, both fitted with slots and interceptors, and the pilot had been able to recover from a spin by using ailerons only, keeping rudder and elevator on. The spin was, however, probably still in its initial stages.

Squadron-Leader LUCKING: All, or most, of the models used by the authors were models of aeroplanes which were normally symmetrical until the controls were moved over—and presumably most of the full-scale tests had been carried out on such aircraft—whereas pilots had to use aircraft which might not be symmetrical. Sometimes they were asymmetrical in design to counteract engine torque or slipstream effects, and sometimes an aeroplane, particularly a wooden aeroplane, which had been operating for some time under conditions in which it was impossible to provide first-class maintenance, had its wings warped considerably, to the extent of perhaps 0.5° variation in incidence across the span. In one such case the pilot had reported that, although the machine was easy to fly normally, when it got into a spin it would not come out of it in the ordinary way—and he had only been able to save his neck by means of bursts of engine. Another pilot then operated the machine and reported the same trouble. It was then examined carefully and was subjected to an abnormally careful rigging check, as the result of which it was discovered that the whole of the top plane was in winding to the extent of 0.75°. When that defect was put right, the machine was put into a spin and had come out of it normally. In view of such experiences, Squadron-Leader Lucking asked whether, as the outcome of research, it would be possible to establish limiting rigging tolerances similar to the tolerances applying to an engine, so that one would know that an aircraft would behave normally if its tolerances were within the prescribed limits.

Mr. H. C. H. TOWNEND: With reference to the authors' suggestion that a biplane with a very large forward stagger might be made unspinnable if loaded at the wing tips, he supposed that if the stagger were made infinite one would get something approximating to a monoplane, and he would like to know if a monoplane could be made unspinnable more easily than a biplane.

Flying-Officer WHITTLE: He had gathered that if a machine got into a spin from which it was difficult to recover, an alteration of the position of the C.G. and a reduction of the pitching inertia couple might help. He suggested that if a test pilot found difficulty in recovering from a spin he might with advantage try to persuade his passenger to step over the side and jump off, and then make another attempt at recovery.

The CHAIRMAN: There had been very many cases in which a machine had come out of a spin only when the pilot had stood up and begun to handle his parachute. That seemed to be attributed by some to cussedness in the machine itself.

Mr. S. B. GATES (Royal Aircraft Establishment): By an extraordinary inadvertence, the responsibility for which he must share, since he read the manuscript without noticing the omission, the name of the late K. V. Wright occurs nowhere in this paper, although not a few pages of it could hardly have been written had he not contributed to the research. Wright was for some years in charge of the development of the complicated full-scale technique for the measurement of spins, and he was a pioneer in working with spinning models. An example of his exceptional physical insight was his discovery of the virtual moment effect in the determination of moments of inertia at a time when dis-

crepancies in the experimental results were puzzling everybody. His work was done at a stage in the research when there was a great deal more labour than scientific reward in the shape of clear-cut results; the reports in his name are an altogether inadequate measure of the work he did; he has died without realising its fruits. His work and his worth live, however, in the minds of his friends and associates; and certain of his ideas, which he left undeveloped, will form part of our equipment for the future.

Mr. A. E. WOODWARD-NUTT (Marine Aircraft Experimental Establishment): There is one point on which he should like to join issue with the authors of this paper. They recommend pilots to apply full opposite rudder before easing the stick forward in order to recover from prolonged spins which have tended to become flat. They state that " misapplication of the elevators, such as might easily occur at the hands of an inexperienced or bewildered pilot may lead to spinning conditions of a dangerous character on an aeroplane which can normally be regarded as perfectly safe," and from the context it is clear that the misapplication referred to is the pushing forward of the stick *before* applying opposite rudder. They admit that this can easily occur, and the point is emphasised by their story of an exceptionally experienced and cool-headed test pilot, who, in a prolonged intentional spin, found that he had become so confused that he was applying rudder *for* the spin when attempting recovery. Surely, therefore, an aeroplane should not " normally be regarded as perfectly safe " if recovery from a spin may depend on whether opposite rudder is applied before the stick is moved forward, or *vice versa*. Many pilots have been trained to recover from spins by pushing forward the stick and applying opposite rudder simultaneously.

Difficulty in recovery from a spin is a very different matter for an inexperienced pilot who may unintentionally have entered a spin at a relatively low altitude, than it is for a highly experienced test pilot who is deliberately performing long spins from a height which allows him ample time to study the effect of control movements. Unless both pilots have an equal chance of recovery, he submitted that the aeroplane should not be called perfectly safe.

Safety is admittedly a relative term, but perfect safety is not. It seemed to him that there are only two kinds of aeroplanes which can justifiably be called perfectly safe, as regards spinning. One is unspinnable, and the other has to be held into a spin and will recover immediately that the aeroplane controls are released.

At the present time, for various reasons, they did not as a general rule produce aeroplanes of either of these types. On the contrary, it must be admitted that the margin of safety in a great many types of aeroplanes is very small. Anyone familiar with full-scale spinning tests knows how slight a modification will sometimes render a relatively safe aeroplane dangerous, and *vice versa*. He had no wish to imply that spinning is necessarily a highly-dangerous pursuit. He did not consider that it is. But it is wise to bear in mind the smallness of the margin—a margin which, he might add, the valuable work of the authors of this paper has done much to define. The definition, however, is still far from complete.

Might he, therefore, with all deference, suggest that for a scientist the term " perfect safety," as applied to spinning, is at least premature.

REPLY TO DISCUSSION

Mr. IRVING: He would first comment on the remarks made concerning the desirability of making aeroplanes unspinnable, and the Chairman's use of the expression " tails up," as summarising the results of the research work. He added to that the consideration that when dealing with spinning one must not consider either the aerodynamic properties of the aeroplane by themselves, or the moments of inertia by themselves, as being good or bad, but must always

couple them together. Certain combinations were good, and certain combinations were bad, and designers, acting on the hint given in the paper, might do something in the way of working in the inertias and the aerodynamics together so thaf those factors helped each other—the inertias could help the aerodynamics, so as to obtain a good combination rather than a bad one. It was difficult to control the inertias, of course, for they were more or less fixed by design, but one could sometimes alter stagger at the last minute without altering the inertia moments very much. As to the Chairman's question concerning the reason why the models in the vertical tunnel did not foul the walls, he said, amid laughter, that he had heard it explained but had forgotten the explanation. The use of a vertical tunnel, instead of a horizontal one, did economise space, and he agreed also that it had definite advantages in working. At the National Physical Laboratory experiments were carried out in horizontal tunnels in which the models were constrained, and it was really very awkward to have the lift on the model travelling in the radial direction and gravity pulling downwards all the time. With a vertical tunnel the work would be easier.

He did not think one could give a general reply to Capt. Barnwell's question as to whether, when a machine was unwilling to go into a spin but was vicious when it did spin, that was due to some unusually large inertias. It might be due to the A-B or the C-A, but one could not generalise. Replying to Capt. Barnwell's question about sideslip producing a big rolling moment, and the comparison of a static rolling moment with a moment due to rotation, he said the idea was that comparatively small sideslip would produce a big rolling moment; the rolling moment produced by, say, 10° sideslip was quite enough to overcome a very big auto-rotative tendency in an aeroplane. So that a very big auto-rotative tendency at no degrees yaw condition would quite disappear as the result of yawing at, say, 10°. That was tried a good many years ago in the case of the " Bantam," which had huge auto-rotational speeds, but which, when yawed, became neutral.

It was true, as Capt. Barnwell suggested, that comparison was made in the paper between the rolling moment due to sideslip without rolling, and the rolling moment due to rolling. It had been found, however, that the large rolling moment due to sideslip generally persisted when a rolling motion was superposed on the sideslip, although with an important reduction under certain conditions, particularly if there were no dihedral angle.

With regard to engineering difficulties, he said that at the beginning of any model experiments the engineering considerations were left out deliberately. The object was to try first to obtain some solution or possible solution of the problem in mind, and then afterwards to consider whether it was practicable. He considered that that procedure was quite sound.

With regard to the point made by Capt. Hill, that there must be a virtual mass effect in the spin itself, and the question as to why it was ruled out of the experimental determinations of the moments of inertia, he said the answer was that in the results obtained from the rolling experiments the virtual mass effects were included already; the air was being carried round with the model in the actual experiment, so that if one included virtual mass in the experimental determination of the moments of inertia one would be taking it into account twice. As to the suggested omission of the tailplane, he said he would very much like to think about the spinning properties of the Pterodactyl, but felt that he could not begin to think about them until he had got the moments of inertia.

He was interested in Mr. Stevens's remarks concerning bringing a machine out of the spin on the ailerons only, and confessed that he had forgotten about the original slot and aileron control bringing the " Avro " out of the spin. He thought, however, that the spin of the "Avro" never became flat. The suggestion to twist the tail of an aeroplane was an excellent one—leaving out of account the engineering considerations. He referred the suggestion to Capt. Barnwell.

He could not give a definite answer to Mr. Nayler's question as to whether or not there was any connection between irregularity of spin and difficulty of recovery. He was glad Mr. Nayler had mentioned cases in which machines were worse from the point of view of spinning when the centre of gravity was forward than when it was further back; calculations made by himself and his colleagues showed that that was quite possible with certain combinations of stagger and moments of inertia. There was a tendency for aeroplanes to be worse with the centre of gravity forward if they had negative A-B and large forward stagger. It was rather interesting to deduce from that the fact that such aeroplanes, if they were bad, might be improved by the addition of floats, because floats produced a very large positive pitching moment about the stall, *i.e.*, they were equivalent in effect to a large backward movement of the centre of gravity. He mentioned this because there might be a danger of damning floats altogether as factors which always produced bad results; they need not produce bad results always. The placing of horns on an aeroplane, possibly a parachute on one wing tip, might be most effective; indeed, he had heard that one pilot was thinking of trying some such device, but he had not heard what results had been obtained thereby.

Dealing with Dr. Lachmann's question as to whether Bryant's conclusion, concerning the effect of a rolling moment applied against the spin, would hold if the auto-rotative properties of the wings were destroyed, Mr. Irving said he thought that it would. When one sideslipped an aeroplane a rolling moment was produced which would make it rotate even though there were no auto-rotative tendency as generally understood. If there were no rolling moment due to sideslip Mr. Bryant's conclusion would be different. He had not carried out experiments on interceptors with slots fitted in front of them, and the only experiments he had carried out with interceptors were confined to a fairly flat spin. The results of the experiments on flat spins were not very encouraging, but he believed the results on steep spins would probably be very different. In any case, he had noted Dr. Lachmann's assurance that very different results were obtained in the case of a steep spin.

In reply to Squadron-Leader Lucking's remarks concerning unsymmetrical aeroplanes, he said that quite a lot of aeroplanes seemed to be just on the borderline, so that quite a little would render them really safe or really dangerous. That must be the reason why comparatively small differences seemed to produce an aeroplane dangerous in the spin.

Finally, he dealt with Mr. Townend's suggestion that possibly an unspinnable aeroplane would be one in which positive A-B was combined with large forward stagger, and the question as to whether the monoplane was not equivalent to an extreme case of stagger. His reply was that there might be a stage in between, where the stagger would be extreme, the machine giving more stability in roll than would a monoplane, but there was no doubt that the monoplane results were very similar to those obtained with a biplane having a stagger of about 30°.

Mr. STEPHENS: The reason why models in a vertical wind tunnel did not foul the walls, was, he imagined, the effect similar to that experienced by aeroplanes flying in formation; when the wing of the model came close to the wall there was an increase of lift, which tipped the model inwards and caused it to sideslip slightly towards the centre of the tunnel. When flying along the beach at Brighton one noticed a similar effect; the effect of the continuous cliff on one side was to give the aeroplane a rolling motion away from the cliff.

Dealing with Captain Hill's question concerning virtual mass, he said they analysed the steady spin by balancing the gyroscopic moments—which were, of course, due to the true moments of inertia—against the sum of the aerodynamic moments. These were, in a sense, virtual mass effects. As virtual mass corrections could be as much as 30 per cent., it was of the greatest importance to apply them correctly.

He disagreed with Mr. Stevens' contention that an experiment in which the machine spun right to the ground was not inconclusive. Some pilots entirely lost their heads in such circumstances—though he did not say that that applied to the pilots at Martlesham—and their statements did not necessarily present very accurate accounts of what they had done.

Joint Reply to Written Contributions to the Discussion

We cannot admit Mr. Gates to any share in the responsibility for the unfortunate omission in the original paper of any reference to the work of the late K. V. Wright. We have tried to make good that omission by a note added at the end of the paper, and should also like to endorse Mr. Gates's appreciation of Wright's work.

With regard to Mr. Nutt's remarks, what we meant to imply was that certain aeroplanes which have been passed as safe for spinning may possibly be liable to get into a dangerous spin if the elevators are held forward during a prolonged spin. Accordingly, we suggested that pilots should be warned against this danger; a more comprehensive suggestion would have been that all machines should be tested for spins with elevators down before they are passed for service.

PROCEEDINGS

FOURTH MEETING, FIRST HALF, 67TH SESSION

The Fourth Meeting of the First Half of the 67th Session of the Royal Aeronautical Society was held in the lecture theatre of the Royal Society of Arts, 18, John Street, Adelphi, London, W.C.2, on Thursday, November 19th, 1931, when a paper on "Aircraft Vibration," by Mr. H. Constant, M.A., A.F.R.Ae.S., was read. The President of the Society (Mr. C. R. Fairey) was in the Chair.

The PRESIDENT: Vibration seemed inseparable from the operation of ships, trains, aeroplanes, motor cars and every other means of transport, but he believed that only in respect of the aeroplane had really serious scientific study been devoted to the elimination of vibration. It was one of the principal sources of discomfort to passengers in aeroplanes, and it was one of the greatest sources of danger to the aeroplane structure, so that its elimination or reduction was of the greatest importance to the future development of the flying machine. Mr. Constant, after graduating at Cambridge University, had worked for a year on the problem of crankshaft stiffness, and for three years since then had devoted himself to an intensive study of the problems of vibration in aircraft, at the Royal Aircraft Establishment.

Mr. Constant then read his paper.

AIRCRAFT VIBRATION

BY

H. CONSTANT, M.A., A.F.R.AE.S.

Introduction

In the early stages of development of every form of transport, the pioneers have cheerfully undergone great extremes of discomfort and unpleasantness. As the sense of novelty and adventure began to lose its early appeal a slow but insistent demand for greater comfort arose. To-day, there is a growing tendency to take aeronautics as a matter of course, and an increasing demand for those standards of comfort which have become the rule in the older methods of transport.

The two factors that most seriously prejudice one's comfort in aerial transport are probably noise and vibration. The problem of aircraft noise was laid before you last session by Dr. Davies.

The engineer has seldom a good word to say for vibration. In all his schemes it comes to cross him like an ill-tempered fairy godmother. In the days when men designed by eye and worked in tenths of an inch instead of in thousandths, vibration was more of a nuisance than a serious problem. To-day, when factors of safety are being pared to the bone, when weight is regarded with a jealous eye and members are being stressed right up to the limits of their capacity—to-day, vibration is rapidly becoming a definite limiting factor in design, and the problem of vibration in all its varied forms, one of the most pressing that the engineer has to face.

In aircraft, vibration is a double nuisance. Not only does it unpleasantly affect the passengers and pilot, but it causes additional and unnecessary stresses in the structure and fittings of the aircraft and engine. As the detection of the existence of excessive vibration is usually through its physiological effect on the occupants of the aircraft, it is from this aspect that the problem has in the main been viewed and from this aspect it will here be presented to you. The whole of the investigation here described was carried out at the Royal Aircraft Establishment.

The Cambridge Vibrograph

The first requirement in any experimental investigation is an instrument capable of measuring the phenomena involved. At the commencement of this work no instrument was available suitable for the measurement of the vibration

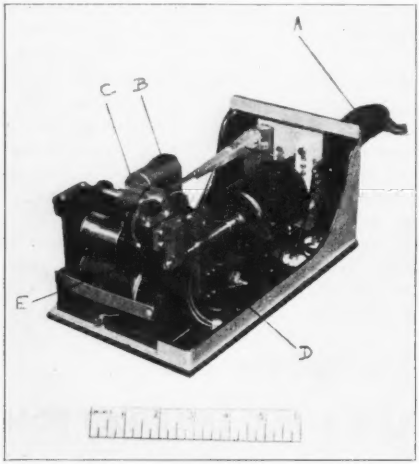


FIG. 1.

of an aeroplane in flight. After gaining experience with unsuitable instruments the vibrograph shown in Fig. 1 was finally obtained. This instrument was constructed by the Cambridge Scientific Instrument Company on the principle of their standard portable vibrograph, a few modifications being made to R.A.E. specification. In essentials it consists of a heavy casing held by the operator by the handle A so that a projecting pin (not shown) rests on the object whose vibrations are to be recorded. Inside the casing a system of linkages connects the operating pin to a steel stylus B, and magnifies the movements of the pin seven times. The stylus records the movements by pressing a groove with raised sides in a strip of celluloid C, which is drawn beneath it by a small 12-volt electric motor. An additional stylus operated by a solenoid D records time markings on the under side of the celluloid. The contacts for the time markings are obtained from a 1/50 second tuning fork. In the figure the instrument is shown with the cover removed. The celluloid carrier E takes a roll of about 600 cms. which passes at a speed of some 2 to 3 cms. per second. The instrument, being hand held, has no true natural frequency. Owing to the impossibilty of keeping a uniform pressure on the operating pin the zero line does not remain steady but fluctuates with a frequency which varies from 300 to 400 per minute, according to the rigidity of the method of holding. Records of vibrations below

about 1,000 per minute are thus of doubtful accuracy. The upper limit of the instrument's reliability occurs when the acceleration applied to the operating pin by the vibrating member exceeds the restoring acceleration provided by the springs in the linkage system. This limit has not been reached on any of the tests carried out, which involved accelerations up to 20g. It is claimed by the makers to be above 100g. A typical vibrogram obtained by enlargement from the celluloid record is shown in Fig. 2. In this figure the magnification has been increased by enlarging to a total of 145. The great majority of the experimental observations referred to in this paper have been made by means of this vibrograph.

Analysis of Vibrograms

The vibrograms obtained usually consist of several combined simple harmonic vibrations of different frequencies and amplitudes. Separation of the component harmonics by Fourier analysis is generally impracticable, not only on account

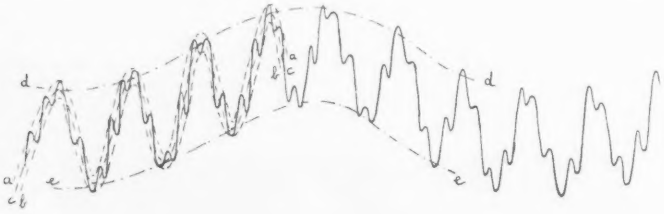
FIG. 2.

of the excessive time required, but also owing to the irregularity of many of the records. These harmonics have therefore been separated by a process of inspection and construction of envelopes. The method is illustrated in Fig. 3. The first step in the process consists in the separation of the harmonic of highest frequency by drawing in the envelopes of the peaks of this harmonic as shown by lines "aa," "bb," in Fig 3. The amplitude of this harmonic can then be measured. The mean line "cc" of the envelopes "aa" and "bb" is then treated in the same way, envelopes "dd" and "ee" being drawn in. Thus the next harmonic is separated out and can be measured. The process is continued until all the component vibrations have been eliminated and we are left with a low frequency surge of some 300 to 500 per minute due to the instrument not remaining fixed in space.

The method is obviously only approximate and fails to separate harmonics that have frequencies differing only slightly from each other. It is, however, sometimes possible to effect such a separation by making use of the beating of the two components. Apart from this case of failure the process provides a quick method of obtaining an approximate idea of the values of the more important components of a complex vibration and has given results which compare reasonably well with those obtained by a strict Fourier analysis where such is possible.

Study of Fuselage Vibration

The first step in the investigation was the exploration of the general vibration characteristics of an aircraft. The problem resolved itself into a study of the vibratory motion of an elastic beam of non-uniform elasticity and weight distribution, held at two points by elastically connected supports, and subjected to forces and couples by varying amounts and frequency applied for the most part at or near one end of the beam. The experimental study was begun by forcing and measuring vibrations in a complete Atlas aircraft, mounted in such a manner as to simulate as closely as possible the conditions obtaining in flight.



METHOD OF ANALYSING VIBROGRAMS

FIG. 3.

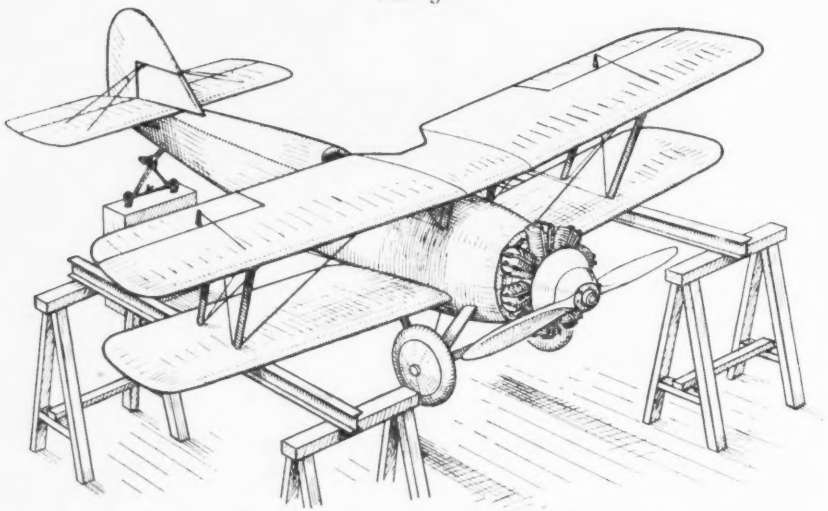


FIG. 4. METHOD OF MOUNTING AIRCRAFT FOR VIBRATION TESTS.

The method of mounting the aircraft is shown in Fig. 4. The machine was supported on girders which passed beneath its lower wing at the points of connection of the interplane struts. The girders were in turn supported at their ends on wooden trestles. The weight of the aircraft was distributed between the front and rear spars. The tail was kept in equilibrium by a load attached to the tail skid by shock absorber cord. Beneath the nose of the engine and

rigidly connected to it was mounted an out-of-balance vibrator consisting of two parallel shafts geared together and carrying a series of adjustable bob weights. By adjustment of these weights a periodic force or couple of any required magnitude could be applied to the aircraft. The vibrator was driven through a flexible drive by an electric motor with a speed range of from zero to 2,600 r.p.m. The natural frequency of the aircraft as a whole on its support was low. Below about 800 r.p.m. the influence of the elasticity of the girders rendered the conditions artificial, but at higher frequencies it is probable that the conditions approximated reasonably closely to those in flight. The vibrator was arranged to produce an harmonically varying force acting in a vertical plane 12 inches in front of the engine mass centre. The amplitude of the force was 470lb. at 1,700 r.p.m. At other frequencies it was different in proportion to the square of the relative frequency.

Vibrograms were obtained showing the vibration of different parts of the fuselage at various frequencies. The principal object of the test was to obtain

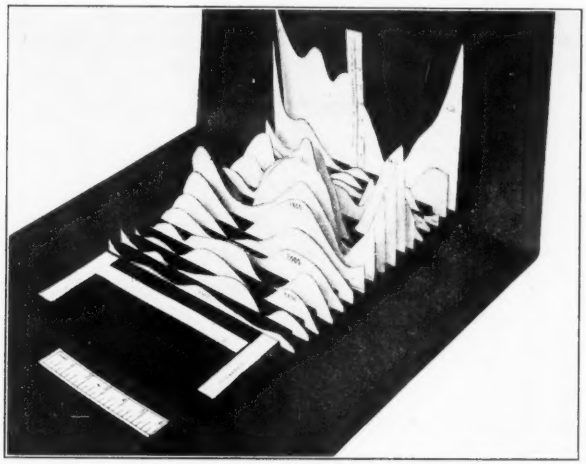


FIG. 5.

the position of the nodes for flexural vibration in the vertical plane and the variation of their position with frequency. These positions were obtained by measuring the amplitude of vibration at various points along the lower port longeron at different speeds. A few check observations were made on the starboard longeron which confirmed that no appreciable torsional movement was occurring. By this means elastic curves showing the manner in which the fuselage deflected under vibration were obtained at several speeds. The complete set of elastic curves can only be properly studied by means of a three-dimensional surface and a model showing this is given in Fig. 5. The actual elastic curves at a few selected speeds are shown in Fig. 6. From a study of these figures a number of facts will at once be noted.

The fundamental two-node natural frequency of the fuselage occurs probably between 600 and 800 r.p.m. Its position could not be fixed definitely owing to the vibration of the supporting girders obscuring the results. The three-node vibration occurs at about 1,600 per minute; four-node at 2,200 per minute; five-node above 2,600 per minute. There is frequently a node close to the engine centre of mass. The variation in the position of this node was not fully studied as vibration was measured only as far as the engine backplate. As the frequency

increases the nodes appear to move down the fuselage towards the stern post, becoming closer together as they do so, fresh nodes appearing at the front end of the fuselage. There is nearly always a node close to the wing attachments, usually between the two spars, and another node some 3ft. to 6ft. in front of the stern post. Vibration in the front cockpit is usually less than in the rear cockpit.

The results shown in the figures were obtained with the axis of the airscrew blades horizontal. A change of this axis to the vertical position results in a different mass system, the changed effective inertia of the airscrew altering the frequency of each mode of vibration. A completely different set of elastic curves is thus obtained. When the airscrew is rotating the elastic curve is a complex combination of the two and consists, in addition, of the superposition of the component elastic curves corresponding to each constituent of the airscrew and engine forcing impulses.

The position of the airscrew at the epoch of the vibration is thus important and we are led to expect that the vibration in an aircraft can be modified by altering the position of the airscrew relative to the crank throw. This has been found to be so, but has not yet been systematically studied.

In addition to these Atlas tests in which vibration was forced by an out-of-balance vibrator, measurements have been made of the flexural deformation of

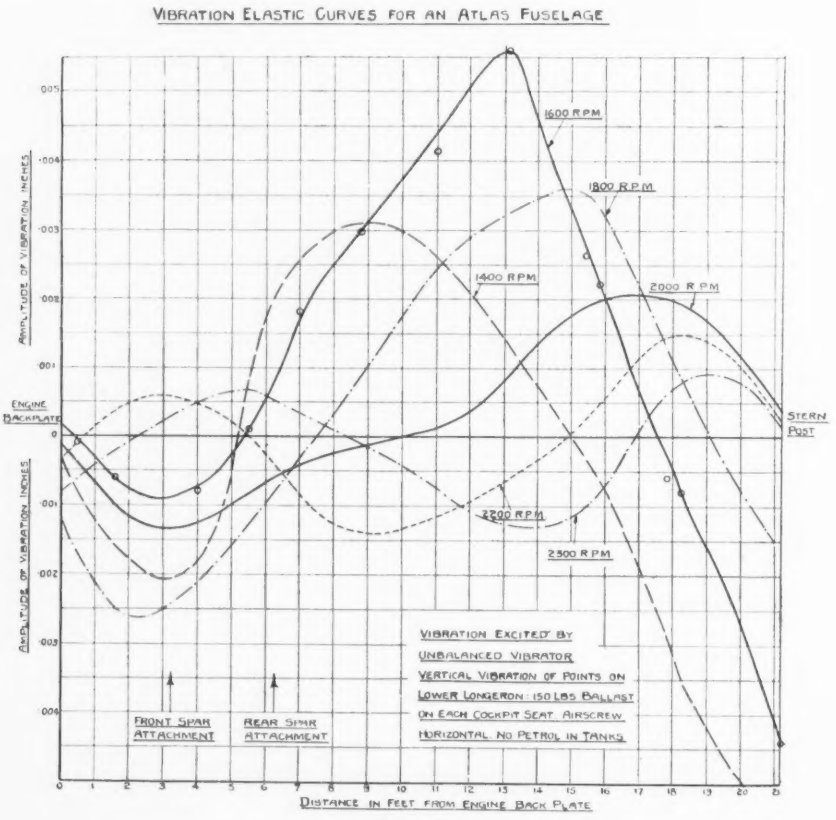


FIG. 6.

fuselages when subjected to the vibration caused by the engine and airscrew rotating. As an example, the elastic curve of the fuselage of a two-seater aircraft with a radial engine is shown in Fig. 7. The aircraft was standing on the ground and the vibration in a vertical plane of different parts of one of the longerons was measured at an engine speed of 1,200 r.p.m. In the figure the vibration shown is that caused by the secondary unbalance of the engine. There are, of course, other vibrations of different frequency superposed on it, but these have been omitted from the figure for the sake of clearness. The frequency of vibration is 2,400 per minute and there are five or six nodes along the fuselage. As the tail skid was on the ground a node is induced at the tail which would probably not be there with the aircraft in flight. It was not possible to measure the vibration forward of the wings. The tendency of the nodes to occur at the bay points should be noted.

A number of flexural deflection tests carried out on air-frames have given stiffness figures which, when combined with the aircraft mass system, give values for the natural frequencies of the aircraft. For the fundamental two-node flexural vibration in a vertical plane the natural frequency appears to lie in the region of 400 to 800 per minute. Taking as a mean value 600 per minute and

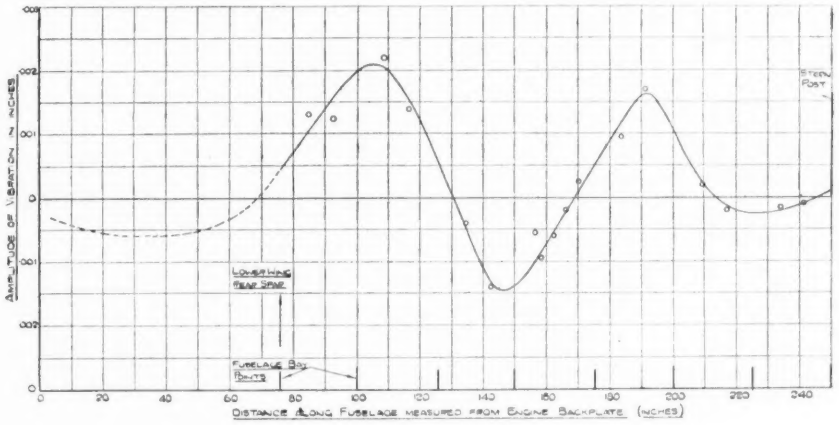


FIG. 7.

referring back to the values for the 3, 4 and 5 node vibrations of the Atlas, we arrive at the conclusion that the natural frequencies of 2, 3, etc., node vibration bear to each other the approximate ratios :—

$$n_2 : n_2 : n_4 : n_5 : \quad 1 : 2\tfrac{1}{2} : 3\tfrac{1}{2} : 4\tfrac{1}{2}$$

the fundamental n_2 being in the neighbourhood of 600 per minute.

We have so far considered only flexural vibration in a vertical plane. The characteristics of the flexural vibration in the horizontal plane appear to be similar, but our knowledge with regard to them is still incomplete.

Torsional deflection tests have been carried out on the engine mounting and rear fuselage of a metal Wapiti. The results of these tests combined with a knowledge of the inertia moments of the principal masses of the system have made it possible to make an approximate calculation of the natural torsional frequencies of the fuselage for the lower modes of vibration. Considerable doubt exists on such points as the amount of flexibility occurring between the fuselage and the effective inertia of the wings; the flexibility introduced between the engine and its mounting by the engine mounting plate, and the method of

idealising the aircraft mass system to make it amenable to mathematical treatment. The calculated natural frequencies for single or two-node vibration are 400 per minute and 1,140 per minute, respectively. No calculation has yet been made as to the frequencies of higher modes of vibration. There is in each instance a node close to the points of attachment of the wings and for two-node vibration there is a second about one-quarter the length of the fuselage, measured from the tail. It is hoped that further work will define the torsional resonant frequencies more exactly and throw some light on the relative importance of the torsional and flexural vibrations of the fuselage.

The Physiological Aspect of Vibration

Some knowledge of those characteristics of vibration which most affect the human frame was necessary before it was possible to decide what types of

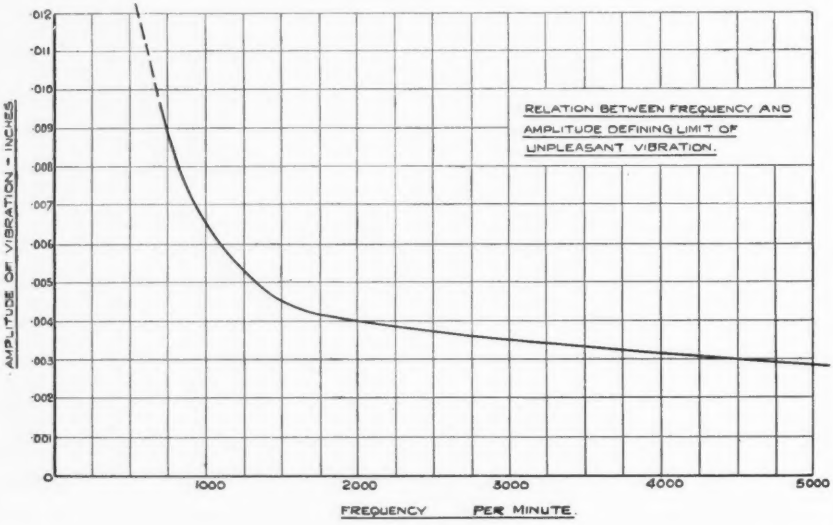


FIG. 8.

vibration were particularly unpleasant to the occupants of an aircraft. Accordingly, a simple contrivance was arranged whereby an observer could be subjected to a vibration whose amplitude and frequency could be altered at will. This consisted of a wooden beam hinged to a heavy bed-plate at one end and mounted at the other on an eccentric driven by an electric motor. The amplitudes of movement of the beam thus varied from zero at one end to a maximum of about 0.10 inches at the other end. An observer was seated on the beam and subjected to vibration of various amplitudes and increasing frequency and attempted in each instance to state when the amount of unpleasantness reached an arbitrary level fixed by himself. It is obviously extremely difficult to obtain consistent results from such an unreliable measurement of unpleasantness. The result of making a large number of observations, however, has been taken as giving a rough indication of the variation of the effects involved. To give the same degree of unpleasantness the maximum permissible amplitude of vibration at a given frequency was found to vary considerably according as the observer was sitting or standing on the beam, and on the particular attitude he adopted in each posture, but the variation with frequency of this amplitude was in all instances of a similar nature.

In Fig. 8 a curve is shown summarising the results of these tests. It shows the connection between the frequency and the maximum permissible amplitude of vibration without the experience of undue unpleasantness. The shape of the curve was determined from the tests already described supplemented by observations of the effect of the vibration of actual engines. The position of this curve is clearly very uncertain and depends to a certain extent on the susceptibility of the individual to vibration, but some criterion is evidently required and the curve represents the best estimate which can be obtained with the information available up to the present.

A considerable number of records of the vibration in various aircraft have been obtained. In a small percentage of these it has been possible to calculate the value of the force or couple producing the vibration. It has in these instances been possible, therefore, to correlate the magnitude of the forcing impulse with that of the resulting vibration. The relation between these two factors will, of course, depend upon the nearness to which the conditions approximate to those of resonance, and this linking up of cause and effect has only been

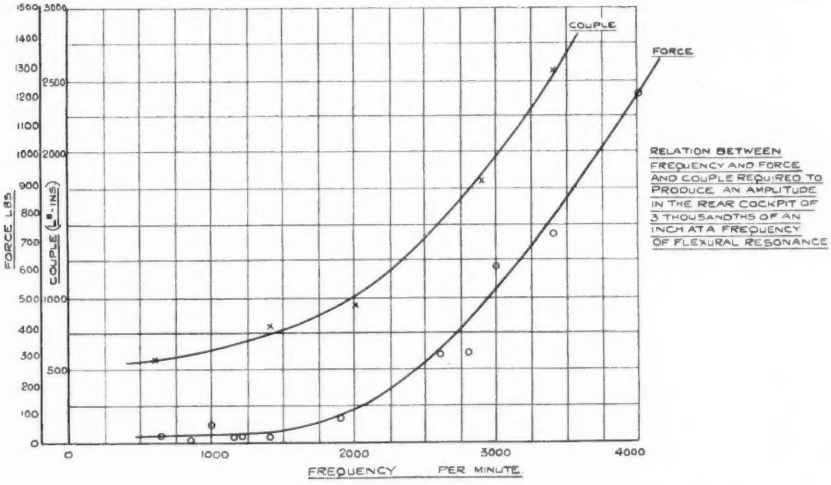


FIG. 9.

carried out at those frequencies when it is apparent from the vibrograms that resonance is occurring. The relations obtained thus give a measure of the magnitude of the applied force or couple that will, when there is resonance at the corresponding frequency, cause a given amplitude of vibration. The results of this investigation will be seen in Fig. 9, where the forces and couples necessary to produce an amplitude of vibration of three thousandths of an inch in the rear cockpit of an aircraft, are shown plotted against frequency. These curves apply strictly only to an aircraft whose all-up weight lies between 4,000 and 5,000lb. For an aircraft of appreciably different weight the force required to cause the same effect will in general be different, but no information is available as to the relation between required force and aircraft size. The points defining these curves are fairly evenly disposed, but unfortunately, few in number, and the curves can only be regarded as temporary approximations which may need adjustment as more data become available. The curves apply only to forces and couples tending to cause flexure of the aircraft in either a vertical or horizontal plane. It has not yet become possible to correlate the magnitudes of torque reaction couples with the resulting torsional movement of the fuselage.

Assuming proportionality to exist between the forcing impulse and the resulting vibration we can now combine Figs. 8 and 9 to give the maximum permissible flexural force or couple that may be applied to the aircraft without causing the sensation of unpleasant vibration in the rear cockpit. The resulting curves are shown in Fig. 10 and apply, as already stated, to an aircraft of 4,000 to 5,000lb. all-up weight. A brief study of Fig. 10 brings out a number of interesting points.

The dotted line has been drawn proportional to the square of the speed, so as just to touch the limiting force curve. It thus provides at every speed a limit above which unbalance forces will be liable to cause excessive vibration when near the critical speed of 1,500 per minute. No airscrew or engine should cause unpleasant vibration at any speed provided that the forces and couples due to static, dynamic, or aerodynamic unbalance do not exceed 50lb. and 1,150lb. inch under the worst conditions. The maximum allowable force increases more rapidly than the square of the speed, while the maximum allowable couple increases less rapidly, so that if at low speeds an unbalance force is

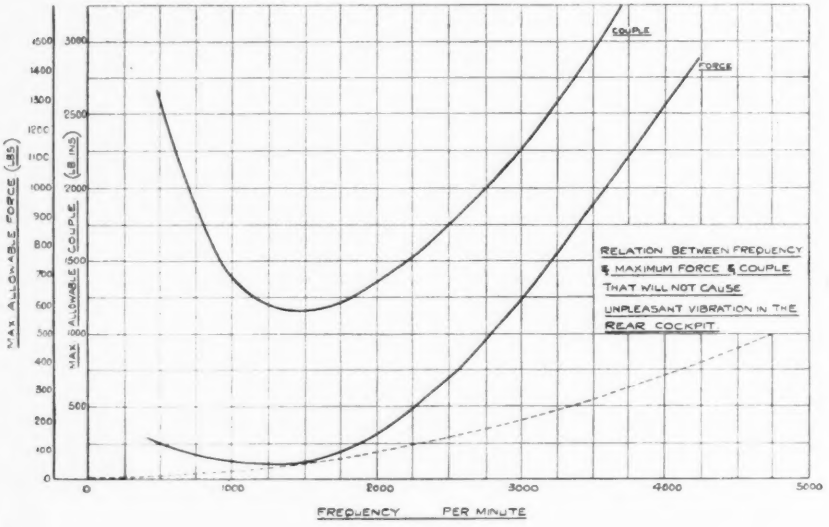


FIG. 10.

insufficient to cause unpleasantness, it will certainly not do so at other speeds, however high; while though a couple at low speed may be insufficient to cause bad vibration, its effectiveness will be increased as the speed is raised. This, of course, is ignoring the tendency of the curves to bend upwards at low speed and applies only to speeds above 1,500 per minute.

Having obtained some idea of the forces and couples that may be tolerated in an aircraft, we proceed to examine the sources of aircraft vibration and the magnitudes of the forcing impulses that may be expected from each source.

The Sources of Vibration—Engine Vibration

The vibration caused by the engine may be due to:—

(*a*) Unbalance of the rotating and reciprocating parts

(*b*) The fluctuations in the torque reaction.

(*a*) The forces and couples caused by the primary and secondary unbalance, that is, the unbalance causing vibration of first and second order, of a number of engines have been collected together and are given in Table I. The chief cause of this unbalance is the presence of an articulated rod system. In all the radial engines considered it gives rise to both primary and secondary unbalance.

It is evident that, as all our results have been developed for an aircraft of some 5,000lb. weight, we must consider our limits of vibration to be applied only to engines of such magnitude as would make them suitable for fitting in aircraft of this size. A consideration of this table will show that in the majority of such engines the forces and couples all lie within the limits imposed by the curves of Fig. 10 which define the maximum permissible magnitudes of forcing impulses.

For the purpose of comparing the relative inherent tendency of different engines to vibrate the idea of specific unbalance has been developed. The specific unbalance force of an engine has been taken to be the unbalance force per unit weight, while the specific unbalance couple has been taken to be the couple divided by the moment of inertia of the engine about an axis through the centre of mass perpendicular to the crankshaft axis. The values of specific unbalance are included in Table I.

TABLE I.

ENGINE UNBALANCE FORCES AND COUPLES.

Designation of Engine.	Primary Unbalance. X Component. Force (lb.).	Primary Unbalance. X Component. Specific Unbalance.	Primary Unbalance. Y Component. Force (lb.)	Primary Unbalance. Y Component. Specific Unbalance.	Secondary Unbalance. X Component. Force (lb.)	Secondary Unbalance. X Component. Specific Unbalance.	Secondary Unbalance. Y Component. Force (lb.)	Secondary Unbalance. Y Component. Specific Unbalance,	Engine Speed (Max) r.p.m.
A	135	0.18	135	0.18	857	1.14	960	1.28	1870
B	188	0.21	188	0.21	1238	1.38	1380	1.53	2200
C	77	0.15	77	0.15	359	0.71	390	0.78	1780
D	0	0	0	0	1315	1.41	3040	3.10	2750
E	0	0	0	0	0	0	0	0	—
	Couple (lb.ins.)		Couple (lb.ins)		Couple (lb.ins.)		Couple (lb.ins.)		
F	418	3.03×10^{-3}	418	3.03×10^{-3}	2130	15.5×10^{-3}	1960	14.2×10^{-3}	1870
G	218	1.33×10^{-3}	218	1.33×10^{-3}	4260	26.0×10^{-3}	4100	25.0×10^{-3}	2200
H	640	1.41×10^{-3}	640	1.41×10^{-3}	4900	10.7×10^{-3}	5230	11.4×10^{-3}	1870

X component along or about axis of master cylinder.
Y component along or about axis perpendicular to that of master cylinder.
All calculations have been made at maximum permissible engine speed.

(*b*) In considering the second source of engine vibration—that of the engine torque reaction—we are on more uncertain ground. For a given engine the values of unbalance are readily calculable and depend only on engine speed. The couples due to torque reaction depend, at a given speed, on throttle opening, altitude, and upon the general tune of the engine. In different engines they are also affected by the number and disposition of cylinders, the firing order and many other factors. Moreover, they are not readily calculable. The whole subject of torque reaction is very involved and cannot be adequately treated here. I shall therefore have to take a good deal for granted in developing the argument necessary to make my points and trust that the discussion will enable me to clear up any individual difficulties.

An harmonic analysis of the torque curve of a single cylinder unit shows that it contains harmonics of every order and half order* which are superimposed

* The order of a vibration is the number of complete vibrations occurring per engine or airscrew revolution. Thus a second order airscrew vibration is one whose frequency is twice airscrew speed.

on a steady mean torque. The values of these harmonics for a few of the cylinders of a nine-cylinder radial engine are shown in Fig. 11. The values shown are typical of the engine, the remainder being omitted simply for the sake of clearness. In a multi-cylinder engine the harmonics due to each individual cylinder must be added vectorially in order to obtain the resultant for the complete engine. When added in this manner the harmonics sometimes combine directly in phase, giving a large resultant, and sometimes combine so as to cancel out and give a zero resultant. Others lie between these two extremes and give resultants of various amounts depending on the arrangement of the cylinders and the firing order. If the values of a given harmonic from different cylinders are not equal—as in general they are not—further differences in the resultant harmonic will arise. For example, a decrease of 3 per cent. in the $\frac{1}{2}$ order harmonics of cylinders Nos. 1, 6 and 8 of the nine-cylinder radial engine already mentioned would cause

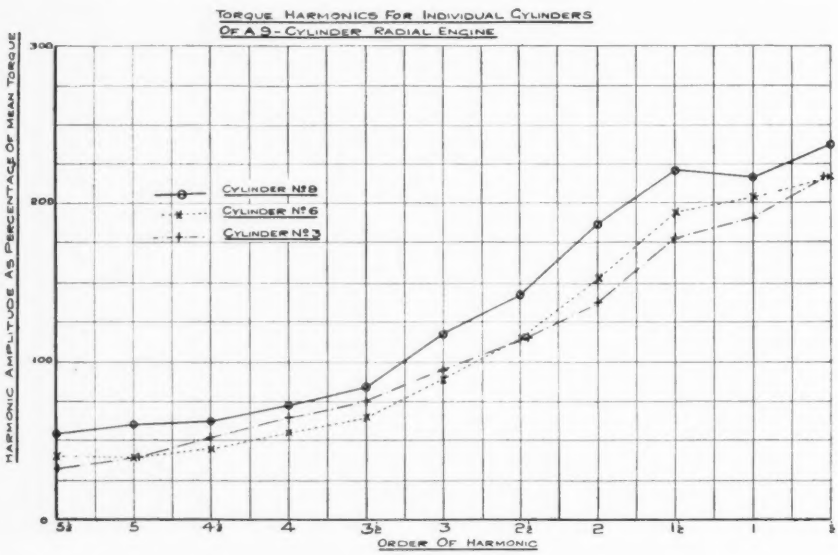


FIG. 11.

an increase in the resultant $\frac{1}{2}$ order for the engine of 50 per cent. The values of all the harmonics, especially those of low order, are continually changing, being extremely sensitive to alterations in the I.M.E.P. of the different cylinders. The resultant harmonics, including inertia torque, for the nine-cylinder radial engine, are given in Fig. 12. In one curve are given the values calculated on the assumption that the values of the components from every cylinder are equal. That is to say, on the assumption that the individual cylinders are giving exactly similar indicator cards, being unaffected by the articulated rod effect, by faulty distribution, ignition or other causes. In the second curve are given the values deduced from an harmonic analysis of a torque curve based on actual indicator cards. The difference between the harmonics occurring in the two instances provides a measure of the divergence from equality of the torque curves of the different cylinders of an engine under running conditions. It will be noted that the most important divergences occur in the first and second orders, both of which are larger in the actual engine than in the ideal case. The $4\frac{1}{2}$ harmonic is large owing to the harmonics of this order of the individual cylinders adding in phase.

In an ungeared engine the torque reaction transmitted to the fuselage consists of the mean torque with the same harmonics superposed as in the engine torque curve. In a geared engine it may easily be shown that the values of the mean torque and of each harmonic are magnified in proportion to the gear reduction ratio.

It will be noted that in Fig. 11 the magnitudes of the various harmonics of the individual cylinder torque curves are expressed as percentages of the mean cylinder torque, and that for the lower orders there are not very great percentage differences between the different cylinders. Thus it appears that the cause of the existence of these harmonics in the complete engine torque is due not so much to differences in shape or phase of the constituent indicator cards as to differences in the mean torques of the constituent cylinders. This suggests that an increase in torque reaction harmonics of low order is attributable to inequalities in the mean torques of the different cylinders of the engine. These inequalities are

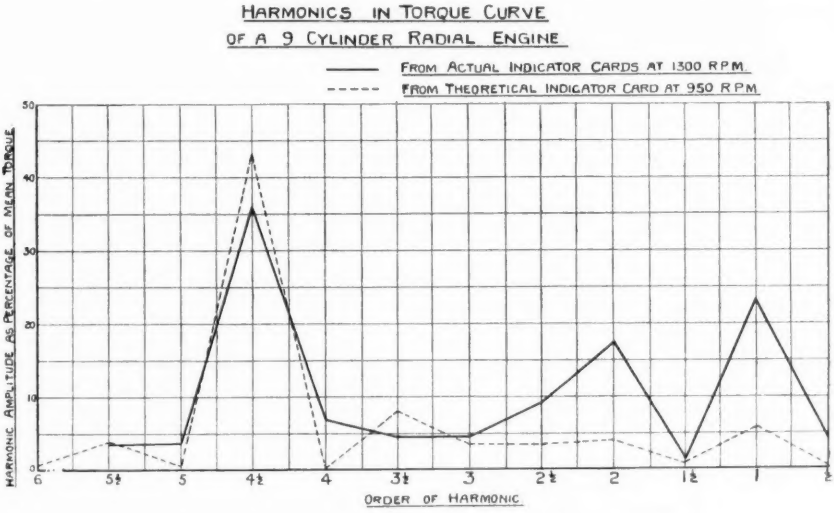


FIG. 12.

partly due to faulty distribution, carburation, ignition, etc., but they may be to some extent inherent in the engine design. For example, in a radial engine, owing to the connecting rod articulation, the ignition advance may be different for each cylinder, varying for one engine over the range 38° to 46°. The effect of this is a variation in the mean torque of individual cylinders and the appearance of low order harmonics however perfect the distribution may be. It is to be expected, therefore, that, other things being equal, the torque reaction of a radial engine with articulated connecting rods will contain low order harmonics of larger values than will the corresponding engine with forked connecting rods. Derangement of the equality of the different cylinder torque curves by excessive weakening of the mixture, by partial or complete failure of ignition in one or more cylinders, or by varying compression in the different cylinders, may cause large increases in torque reaction vibration.

It has, unfortunately, not been found possible to draw up a definite scale of limiting values for the couples due to engine torque reaction, owing partly to the difficulty of associating a given vibration with a definite forcing couple, and partly to our ignorance of the manner of distortion of the fuselage for torsional

vibration. It has been found, however, that, speaking generally, only the harmonics of the torque reaction of orders $\frac{1}{2}$ and 1 need be considered. Vibration due to the $1\frac{1}{2}$ and second order harmonics is only rarely met with. The high frequency harmonics of orders $2\frac{1}{2}$ and upwards cause local vibrations of individual members of the airframe and fittings which are of very small magnitude. These high frequency harmonics do not affect the personnel, but they may be the cause of fatigue in fittings which happen to resonate to their frequency. The failure of harmonics of orders $1\frac{1}{2}$ and over, to cause noticeable vibration, must be attributed to their frequencies being far removed from the resonant frequency or frequencies of the aircraft fuselage in torsion.

Of the low frequency harmonics, that of engine $\frac{1}{2}$ order is probably the most important. Unfortunately its very low frequency has rendered it extremely difficult to measure with the instruments available owing to the super-position of the oscillation caused by the instrument being hand-held. In geared engines, moreover, it is difficult to distinguish from the airscrew first order vibration owing to the gear ratio of existing engines being usually not far removed from 2 : 1. Our information with regard to engine $\frac{1}{2}$ order vibration is therefore very limited, but there is little doubt that this is one of the most noticeable of vibrations. It is probably the main cause of " roughness " when an engine is out of tune and is the principal cause of the blurring of aerial photographs. It may cause amplitudes of longeron vibration exceeding 15 thousandths of an inch in extreme cases. In engines having master and articulated connecting rods, it is accentuated by the differences in ignition advance between the different cylinders. The first order vibration is less important than the $\frac{1}{2}$ order, but may in itself cause appreciable vibration, especially in radial engines. It is affected and accentuated by the same factors as the $\frac{1}{2}$ order.

In geared engines the torque reaction may sometimes cause vibration through being amplified by torsional vibration of the crankshaft, but the orders are usually high and the resulting amplitudes tend to be small in consequence. In very bad cases of crankshaft torsional vibration, severe vibration may be transmitted to the engine bearings and thence to the fuselage, even in ungeared engines. In geared engines the passage through the main torsional resonance speed is accompanied by gear rattling caused by torque reversal at the gears. The magnitude of vibration associated with this rattle is normally not large, as in geared engines the main crankshaft torsional resonance speed is very low and the amplitude of the forcing torque is small.

Uneven meshing of gears may produce vibrations of high order (equal to the number of teeth on the pinion, reckoned on the basis of engine shaft and to twice this number). These have revealed themselves on torsiograms but are beyond the power of the vibrograph to detect.

In brief then, the $\frac{1}{2}$ order harmonic of the engine torque reaction may cause serious vibration, particularly if the engine tune is upset. The first order vibration is similarly affected by lack of " tune," but to a lesser degree. Reduction of these sources of vibration will follow on improvements in distribution and ignition.

Vibration due to the Airscrew

General.—This may be considered under seven headings:—

Unbalance
- (*a*) Static unbalance.
- (*b*) Out of alignment.
- (*c*) Out of track.

Aerodynamic
- (*d*) Out of pitch.
- (*e*) Effect of cross wind and turn.
- (*f*) Flutter.
- (*g*) Gyroscopic.

(*a*) *Static Unbalance.*

An airscrew is statically out of balance when its centre of gravity does not lie on its axis of rotation. The result of airscrew static unbalance is a force rotating in the airscrew plane at airscrew speed. According to the standard laid down in Fig. 10 an airscrew would just cause unpleasant vibration at 1,500 r.p.m. if its unbalance were greater than about 12in. oz. It is common to find wooden airscrews running with 8-10in. oz. of unbalance, while occasionally amounts exceeding the limit just given are met with.

(*b*) *Out of Alignment.*

An airscrew is out of alignment when an imaginary line joining any two corresponding points on opposite blades, when viewed in plan, does not pass through the axis of rotation. This is a particular case of static unbalance and produces the same effect. The manufacturing tolerance for wooden airscrews permits of a deviation of the imaginary line mentioned above, of .05 inch from the axis of rotation. This is sufficient to cause a force of 100lb. in an airscrew weighing 110lb. and running at 1,380 r.p.m., a force which is just double our specified limit, as given in Fig. 10.*

(*c*) *Out of Track.*

An airscrew is said to be out of track when corresponding points on the two blades do not rotate in the same plane. The fact of an airscrew being out of track is usually an indication that the mass centres of the blades are rotating in different planes; the consequent dynamic unbalance consists of a couple about an axis perpendicular to the axis of rotation and rotating at airscrew speed. For wooden airscrews the manufacturing tolerance allows of a difference of track of .06in. for airscrews up to 5ft. diameter with an extra .02in. for every 2ft. extra diameter.

In a 12ft. wooden airscrew weighing 80lb. and rotating at 1,380 r.p.m., the allowed tolerance would produce a couple of about 5,000lb. inch, assuming a reasonable form of blade deformation. In the corresponding metal airscrew rotating at the same speed, the allowed couple will be considerably greater. The tolerances are thus insufficient to keep the vibration within the agreed limit of 1,150lb. inch at 1,500 r.p.m. Measurements of out of track have shown the existence of couples of from 3,000 to 8,000lb. ins. in wooden airscrews at max. r.p.m. At 8,000lb. ins. the vibration was so acute as to render the aircraft unsafe for further flights.

(*d*) *Out of Pitch.*

Speaking broadly, the blades of an airscrew may be considered to be out of pitch when their thrusts are unequal. The effect of out of pitch is a couple about an axis perpendicular to the axis of rotation, rotating in the same sense as the airscrew, at airscrew speed. The specified manufacturing tolerance for wooden airscrews of $\pm\frac{1}{2}°$ at the blade tips is sufficient to limit this couple to less than 1,000lb. ins. under the worst conditions. The amount of differential blade twist occurring in flight is normally insufficient to accentuate out of pitch to such an extent as to infringe the limits laid down in Fig. 10. In adjustable pitch airscrews, vibration can frequently be reduced by neutralising one couple by another acting in an opposing sense introduced as a result of putting one blade suitably out of pitch in relation to the other. To effect this it may be necessary in extreme cases to adjust the airscrew blades to a difference of pitch of as much as 1° to 2°.

* If the airscrew is statically balanced both along and perpendicular to the blades, there will be no vibration due to out of alignment, but if the airscrew is simply checked to be correct to drawing within the allowed limits, fairly bad vibration may occur in extreme cases.

(*e*) *Effect of Cross Wind.*

With two-blade airscrews, periodic forces and couples are set up when the airscrew is inclined to the relative wind or is subjected to angular velocity either in pitch or yaw. A theoretical investigation into this subject is contained in R. & M. 642 by H. Glauert. The periodic forces and couples are of airscrew second order and act about a line perpendicular to the axis of rotation and rotating at twice airscrew speed in the same sense as the airscrew. The periodic couples are a source of considerable vibration, but the periodic forces are too small to be important. The aerodynamic couples caused by angular velocity of the airscrew axis are small and may be neglected. We may thus confine our attention to the couples set up when the airscrew axis is inclined to the relative wind, either due to incidence on the climb or to yaw when sideslipping. With airscrews having more than two blades all these periodic forces and couples are absent.

The amplitude of the forcing couple is given by the relation :—

$$M=(550\,\eta PDJ/2\pi V)\,\{\,1/(1-\lambda^2)\,\}\,\alpha \text{ lb. ft.}$$

where M = couple on blades of airscrew in lb. ft.
P = engine b.h.p.
D = airscrew diameter in ft.
η = airscrew efficiency.
V = aircraft velocity in ft./second.
α = incidence on airscrew axis.
$J=V/nD$.
$\lambda=J/J_0$ where J_0 is value of J for zero thrust.

In straight flight the most severe conditions occur when the aircraft is climbing at a large incidence at full throttle. Under these conditions both P and α are large and V is small. With engines whose gear reduction is about 2 : 1 under these conditions couples as great as 6,000lb. ins. may be set up. With ungeared engines the airscrew diameter is less, and η and J are less, with the result that the couples are only about half as great. In straight level flight at full throttle the couples will be negligible owing to the small incidence on the airscrew. As the airspeed diminishes and incidence increases the couples also increase. At cruising speed they would probably be about 1,000lb. ins. for an engine having a gear ratio of 2 : 1, while near the stalling speed they may increase to as much as 2,000 to 3,000lb. ins.

When turning, pulling out of a dive, or sideslipping, the incidence on the airscrew axis may become very large and it is under these conditions that the largest forcing couples are set up. In aircraft fitted with geared engines the couples under these conditions may be as great as 10,000lb. ins., and vibration of great severity will be set up.

We may summarise these remarks by saying that in level flight it is unlikely that the aerodynamic couples on the airscrew blades will cause noticeable vibration except at speeds close to the stalling point. On the climb, on the turn and in certain manœuvres, bad vibration and sometimes very severe vibration may be set up. None of these vibrations will be set up with three or four-blade airscrews.

(*f*) *Airscrew Flutter.*

No tests have been carried out to determine the effect of airscrew flutter on the vibration of aircraft.

(*g*) *Gyroscopic Couples.*

When the direction of the axis of a two-blade airscrew is changing, there exists, in addition to the steady gyroscopic couple, an equal couple about an axis perpendicular to the axis of rotation, rotating at twice airscrew speed in the same

sense as the airscrew. This couple has therefore a frequency corresponding to airscrew second order. When there are more than two blades the rotating couple is zero and there is no vibration of gyroscopic origin.

The magnitude of these gyroscopic couples may be illustrated by an example. In an aircraft turning at a rate of 0.3 rads./second, fitted with a 11ft. 6in. metal airscrew rotating at 1,000 r.p.m., the value of the periodic couple is about 7,500lb. inches. The couple is directly proportional to the rate of turning, the airscrew speed and the polar moment of inertia of the airscrew. With a wooden airscrew the couple will be between quarter and half as great as with a metal airscrew of the same diameter.

It is evident from the above that the gyroscopic couples on a turn or a loop are by themselves sufficient to cause very serious vibration.

Other Sources of Vibration

The only other possible sources of vibration are included under this heading. They are:—

(*a*) Effects of slipstream.
(*b*) Tail and wing flutter.
(*c*) Buffeting.

Neither buffeting nor tail and wing flutter have been considered in this investigation, partly because they apply only to very specialised conditions of flight and partly because their very low frequency would have rendered them impossible to measure accurately with the instruments available. The frequency of tail and wing flutter is of the order of 200-600 per minute and the amplitudes may be very large.

A certain amount of vibration may be caused by the effect of the slipstream on the wings and tail of an aircraft. It has not been found possible to obtain even a rough idea of the forces set up by the slipstream and our only knowledge of the effect has been obtained from the result of vibrograph tests on an aircraft on the ground subjected to the slipstream of another aircraft located in front of it and fitted with a pusher airscrew.

The two aircraft were placed nose to nose, the airscrew shafts being parallel to each other in line and about 8 inches apart at the tips. One aircraft was fitted with a two-blade Leitner Watts airscrew reversed so as to force a slipstream over the fuselage of the other machine. The engine of this machine was stationary so that its entire vibration was due to the slipstream of the rotating airscrew.

The first test was carried out with a two-bladed airscrew fitted to the stationary engine. As it was suggested that this airscrew, being so close to the rotating airscrew might receive impulses from it, a repeat test was carried out with the stationary airscrew removed. The results of the two tests are very similar, and are shown in Fig. 13.

The vibration is of a very irregular character, but some connection could be traced between the frequencies of its harmonics and the speed of rotation of the airscrew. In the figure the vibrations have been classified as first order, second order, etc., of the airscrew according to the ratio of the vibration frequency to the airscrew speed. Further work may show this classification to be artificial, but it has been adopted here for convenience and to bring it into line with the method used on other tests.

The first and second orders are of fairly large amplitudes while there are smaller vibrations of high frequency. The frequency range covered was 400-1,100 r.p.m. corresponding to engine speeds of 750 r.p.m. to 2,100 r.p.m. The vibration is greater in the horizontal than in the vertical direction. Vibration was measured in the rear cockpit, but is not directly comparable with that obtained on the ground with engine running, as there was no one in the front cockpit and the tail was on a trestle to bring the machine into flying attitude.

(Elevators were horizontal.) Nevertheless the speeds at which the first order (of airscrew) is worst agree well with the speeds at which engine half order is worst with engine running on the ground, suggesting that as the engine gear reduction ratio was roughly 2 : 1 the vibration attributed to engine half order may in part be produced by the slipstream. The agreement between airscrew second order in the two cases is not so good, but still noticeable. It is concluded that a considerable amount of aircraft vibration may be attributed to slipstream effect, the vibration being of frequencies corresponding approximately to first and second order of airscrew. The high frequency vibration is probably the natural frequency of fuselage for some mode of vibration, not resonating, but simply excited by the general shaking about of the fuselage.

VIBRATION CAUSED BY THE AIRSCREW SLIPSTREAM

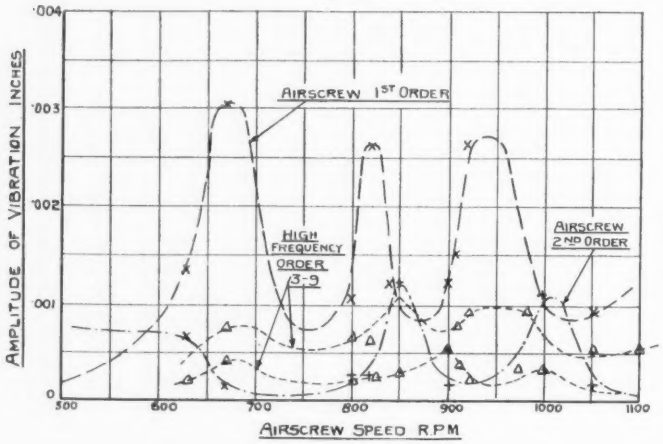


FIG. 13.

The effect of fitting a four-blade airscrew in place of the two-blade would probably be considerable. It should even out the flow of air and considerably reduce the vibration. This slipstream vibration appears to be akin to buffeting.

Having completed a survey of the sources of possible vibration and a consideration of the magnitudes of the forcing impulses involved, we can turn our attention to the effects of these impulses on the aircraft fuselage.

Vibrograph Tests on Aircraft

We propose to consider now the results of vibrograph tests on aircraft on the ground and in flight. We shall take the more important sources of vibration in order and illustrate from the results of the vibrograph tests the vibration produced. It will be convenient briefly to recapitulate the chief sources of vibration. These are:—

(1) Secondary engine unbalance.
(2) The half order harmonic of the engine torque reaction.
(3) The first order harmonic of the engine torque reaction.
(4) Airscrew static and dynamic unbalance.
(5) Effects of cross wind on the airscrew.
(6) Gyroscopic couples on the airscrew.

In every instance the vibration was measured on a longeron or a member attached to a longeron in the rear cockpit. The movement recorded was sometimes in the horizontal and sometimes in the vertical plane.

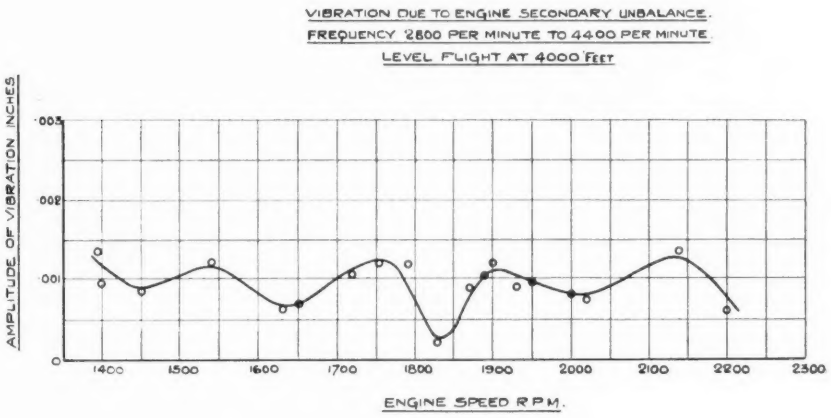


FIG. 14.

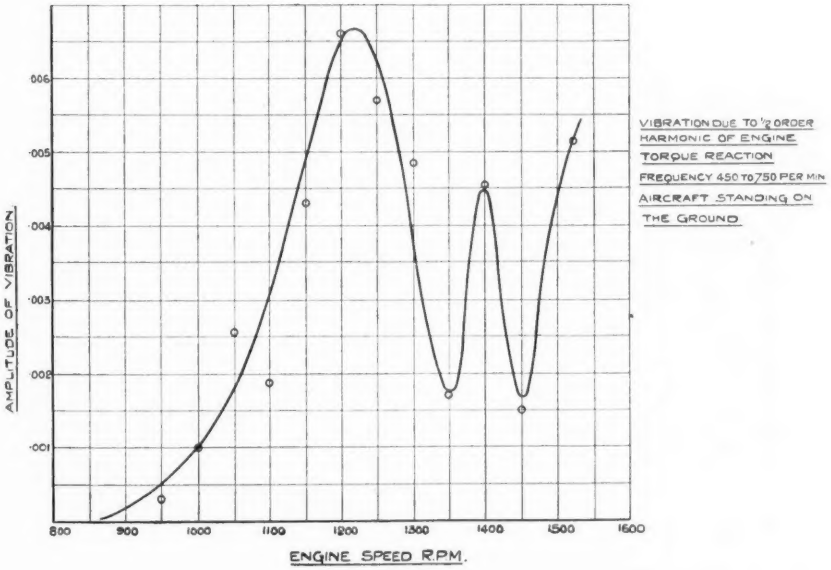


FIG. 15.

(1) An example of the effect of engine secondary unbalance is given in Fig. 14, which shows the vibration in a vertical plane in the rear cockpit of an aircraft with a geared radial engine. The amplitude of vibration is quite small and insufficient to cause inconvenience to the pilot or damage to the structure. This is a fairly typical instance of the effect of engine secondary unbalance. With

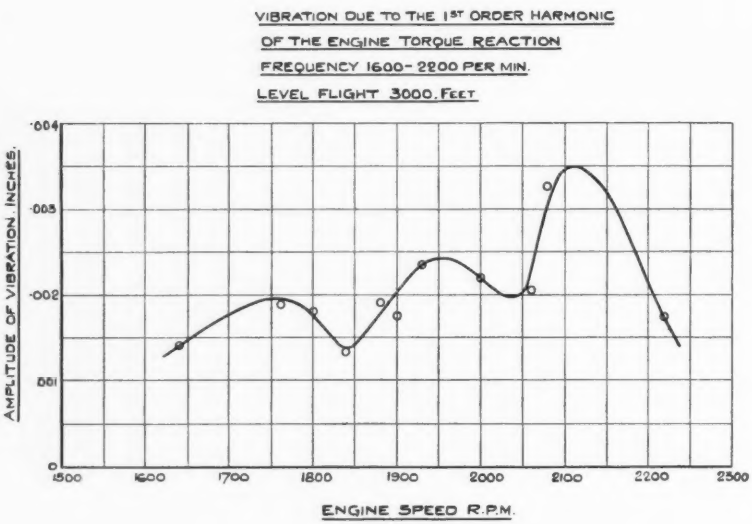


FIG. 16.

Vibration due to airscrew static unbalance of 12in. oz.
Frequency 750-1,050 per min.
Level flight 5,000 feet.

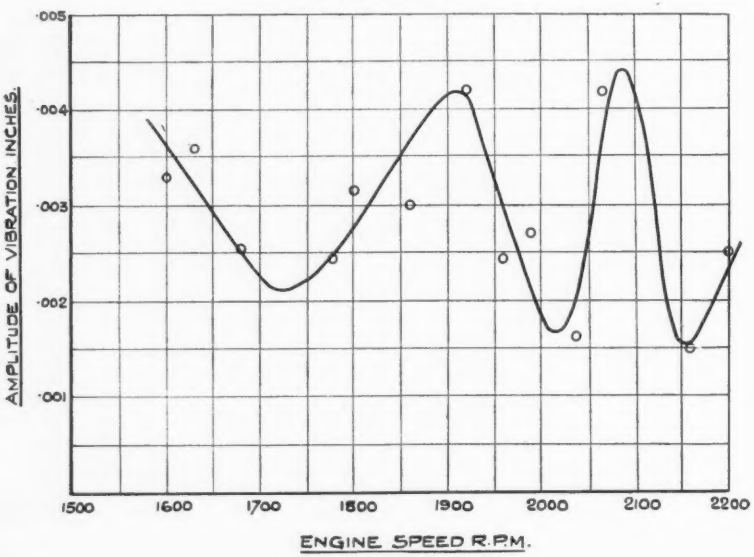


FIG. 17.

engines having larger amounts of unbalance, the vibration will naturally be worse and in some instances is sufficient to cause unpleasantness.

(2) The half order harmonic of the engine torque reaction has been extremely difficult to measure with the instruments available owing to its low frequency, and, with geared engines, the difficulty of distinguishing it from the effect of airscrew unbalance. The effect of this harmonic on an aircraft with an ungeared radial engine is shown in Fig. 15. The aircraft was standing on the ground and the vibration was measured in a horizontal plane. The amplitudes shown should be considered to be only very rough. Considering their low frequency, the amplitudes are not excessive in this particular instance.

(3) The first order harmonic of the engine torque reaction presents considerably less difficulty in measuring. As it is sometimes liable to be confused with the second order vibration of the airscrew in geared engines, an example has been selected from an aircraft fitted with a four-blade airscrew in which the

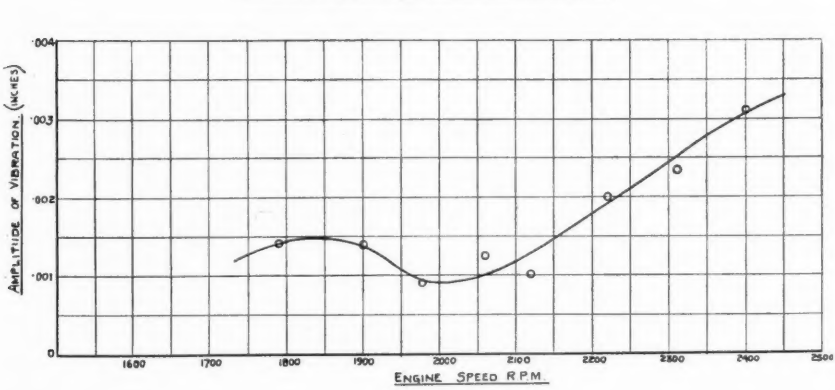


FIG. 18.

airscrew second order vibration is not present. This is given in Fig. 16 which shows the horizontal vibration of a longeron due to the first order harmonic of the torque reaction of a Falcon III fitted in a Bristol Fighter. This vibration is of quite moderate amplitude and is typical of the effect of this forcing impulse.

(4) A curve showing the variation with engine speed of the vibration due to airscrew static unbalance of 12in. oz. is given in Fig. 17. This amount of unbalance is insufficient to give the limiting amount of vibration specified in Fig. 10. The record was obtained from a large single-engined aircraft with a geared supercharged engine and represents vertical vibration of a longeron in the rear cockpit in level flight at 5,000ft.

The vibration caused by out of track of amount 0.20 inch in an airscrew on a general purpose aircraft is shown in Fig. 18. The couple set up by the out of track had a value of about 1,000lb. ins. at 2,400 r.p.m. engine speed. As the figure shows, this couple is insufficient to cause bad vibration.

(5) The vibration caused by the airscrew axis being inclined to the relative wind has proved very elusive, mainly owing to the difficulty in distinguishing it from engine first order vibration in geared engines and engine second order in ungeared. An example of the effect of this vibration is shown in Fig. 19, which has been drawn from the results of a test carried out in level flight on a large single-engined aircraft with a geared engine. The vibration at about 1,600 r.p.m.

slightly infringes the limits specified in Fig. 8. It is probable that a small percentage of the vibration recorded was due to the first harmonic of the torque reaction, but the amount was too small to be separated out by the method of analysis used.

At a given engine speed the couples causing this airscrew vibration increase as the incidence on the airscrew increases. Vibrograms were obtained from another aircraft on partial climbs at 1,800 r.p.m. The results, which are shown in Fig. 20, show the rapid increase of vibration as the incidence of the aircraft and the engine power increase. The vibration makes itself felt at speeds below 90 m.p.h., while near the stalling speed it becomes very pronounced indeed.

(6) The vibrations resulting from the gyroscopic couples on the airscrew blades cannot be separated from those caused by incidence and yaw on the airscrew axis. The two effects must be taken together; they will be considered later under "Vibration on the Turn."

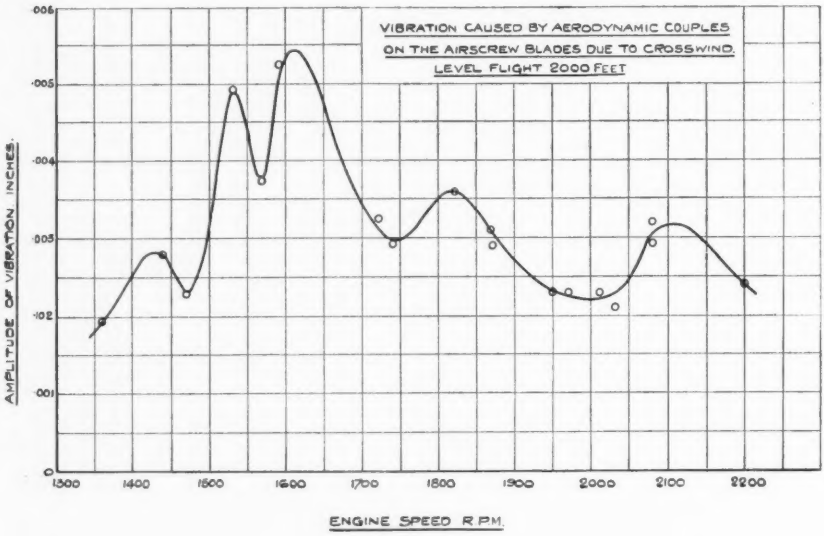


FIG. 19.

The six examples of vibration just considered have each been the result of a single source of forcing impulses. In an aircraft several of these sources are often present together. An idea of the total amount of vibration present at any point of an aircraft can be obtained from Fig. 21. This figure illustrates the different types of vibration existing at a point on a longeron in the rear cockpit of an aircraft with a geared water-cooled engine, when standing on the ground. The vibration was measured in a vertical plane and was recorded on the ground in order to obtain a larger range of engine speed. The vibration in the air is different in detail but similar in general characteristics.

There are four distinct sources of vibration in evidence. There is first of all a very small but high frequency vibration (A) which persists throughout most of the speed range. This represents a local vibration of the longeron responding to the forcing impulses of different harmonics of the engine torque reaction. These local high frequency vibrations are usually present, but are always too small in magnitude to be of any consequence. Secondly, there is the vibration

(B) caused by secondary engine unbalance. This assumes excessive proportions only at low speed where it is in resonance with a three-node natural frequency of the aircraft. Then there is a vibration (C) due partly to the first harmonic of the engine torque reaction, but mainly to the second order airscrew vibration caused by aerodynamic couples on the blades. It has not been found possible to separate the effects of these two sources and they are shown compounded into one curve. Again the vibration is only noticeable in the region of 1,200 r.p.m.,

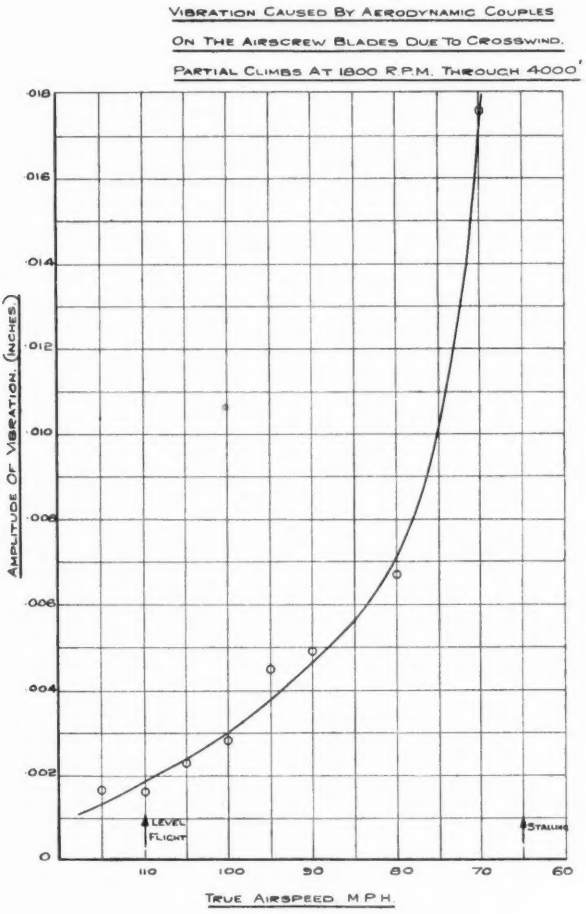


FIG. 20.

corresponding to a three-node mode of vibration of the aircraft. Finally there is a low frequency vibration (D) caused partly by airscrew unbalance and partly by the half order harmonic of the engine torque reaction. In this instance neither of these are important. Before we can be said to have completed our general survey of the effects of the different sources of vibration, we must briefly consider the interference effects between the airscrew and engine when these are rotating at different speeds.

Interference of Airscrew and Engine

When the gear reduction ratio of an engine is not exactly 2 : 1, periodic fluctuations in the vibration experienced by the aircraft occur as the result of interference between the airscrew and engine. This interference arises as the result of two completely independent causes.

The first of these is the well known beating effect caused by the superposition of two vibrations of slightly unequal frequencies. As a result of this, vibration caused by airscrew unbalance will interfere with vibration caused by the half order harmonic of the engine torque reaction. Similarly, vibration due to aerodynamic couples on the airscrew blades will interfere with vibration due to primary engine unbalance and to the first order harmonic of the engine torque reaction. In both these instances the result will be a vibration of fluctuating amplitude and of frequency corresponding to that of the component vibration having the larger amplitude. The frequency of the beat will be equal to the difference between the two component frequencies, that is, the difference between airscrew speed and half engine speed or between engine speed and twice airscrew speed.

The second source of interference occurs only with two-blade airscrews and is caused by the effect on the engine vibration of the varying phase angle between the epoch of that vibration and the position of the airscrew. Consider, for example, an engine driving an airscrew through a reduction gearing of ratio 0.532 to 1. At zero time let a datum line fixed to the engine crankshaft and a datum line lying along the blades of the airscrew, both be vertical. Airscrew and engine are now in phase. As the engine rotates, the airscrew rotates at rather more than half the speed so that at the completion of each engine revolution the airscrew datum line will diverge from the vertical position by an amount increasing with each revolution until the lines are 90° out of phase. With continued rotation of the engine the phase angle will again decrease until after about 16 engine revolutions the two datum lines again become in phase when vertical. This completes a cycle and the process is repeated. The engine datum line may be used to define a vibration of engine origin. Thus at the beginning of the cycle the airscrew was vertical at the epoch of the engine vibration. As the cycle proceeds the position of the airscrew at the epoch of the engine vibration varies continuously through the horizontal to the vertical position again. Now in connection with vibration tests on the Atlas aircraft it has been mentioned that the position of the airscrew greatly affects the character of the vibration owing to the change in its effective inertia altering the mass system. It is also possible that it affects the vibration owing to the alteration in the air damping on its blades as it changes from a position in the plane of the flexural vibration to the perpendicular plane. It appears, therefore, that as a result of this interference, a periodic fluctuation in the amplitude of the engine vibration should result. The frequency of this fluctuation will depend on the particular order of engine vibration concerned. For engine second order vibration its frequency will be equal to twice the difference between engine speed and twice airscrew speed.

This effect has frequently been observed in geared engines and an example of it is given in Fig. 22. This shows the fluctuation in the engine second order vibration due to the modifying effect of the airscrew. The engine speed was 1,980 r.p.m. and the frequency of the fluctuation 245 per minute comparing with the calculated frequency of 250 per minute. The fluctuation can be plainly felt and is a source of considerable unpleasantness. Similar fluctuations have been observed in the vibrations due to other sources. Aircraft with geared engines give out a fluctuating noise of a corresponding frequency which is probably due to the interference effects of noises due to the same sources as the vibrations just considered.

So far we have dealt mainly with vibration in straight flight. We shall now consider briefly the present position of our knowledge with regard to vibration on the turn.

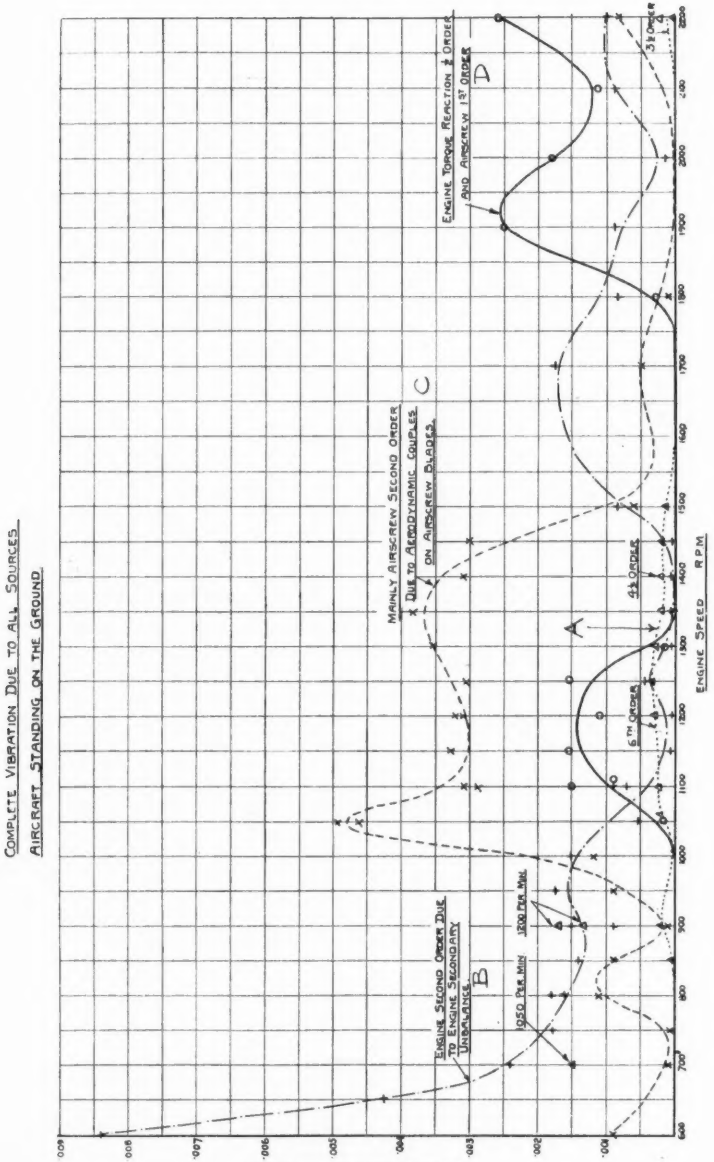

COMPLETE VIBRATION DUE TO ALL SOURCES.
AIRCRAFT STANDING ON THE GROUND
AMPLITUDE OF VIBRATION (INCHES)
ENGINE SPEED R.P.M.
MAINLY AIRSCREW SECOND ORDER
+ DUE TO AERODYNAMIC COUPLES
ON AIRSCREW BLADES.
C
ENGINE TORQUE REACTION 1ST ORDER
AND AIRSCREW 1ST ORDER
D
ENGINE SECOND ORDER DUE
TO ENGINE SECONDARY
UNBALANCE.
B
1950 PER MIN
1200 PER MIN
A
6TH ORDER
4½ ORDER
3½ ORDER
1.4

FIG. 21.

Periodic fluctuation of vibration due to engine secondary unbalance.
Engine speed 1,980 r.p.m.
Frequency of fluctuations 245 per min.
Engine gear reduction ratio 1 : .532.

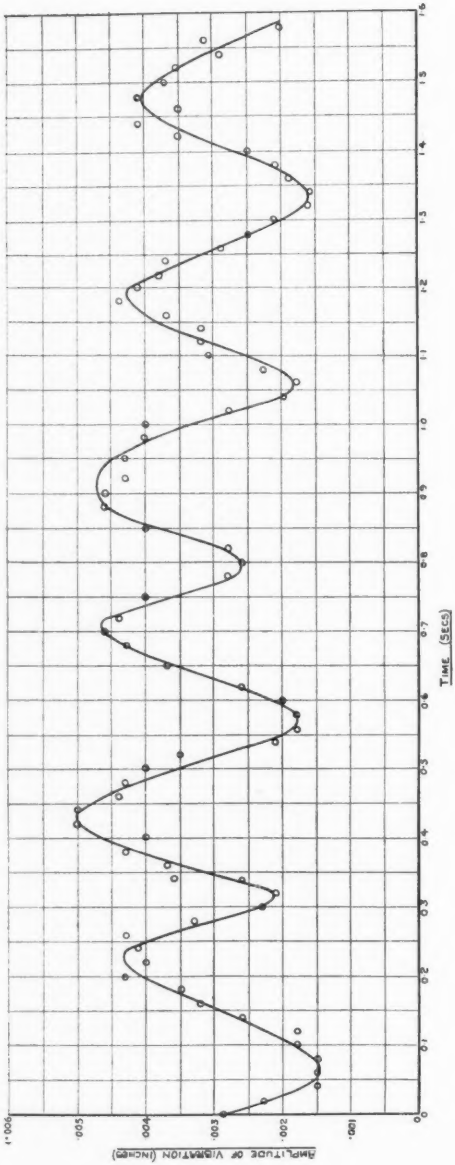


FIG. 22.

Vibration on the Turn

When an aircraft goes into a turn there are four sources of additional vibration :—

(1) Second order airscrew couples of aerodynamic origin due to the increase of incidence on the airscrew axis.
(2) Second order airscrew couples of aerodynamic origin due to yaw of the airscrew axis.
(3) Gyroscopic couples.
(4) Disturbance of engine carburation resulting in increased harmonics of the torque reaction.

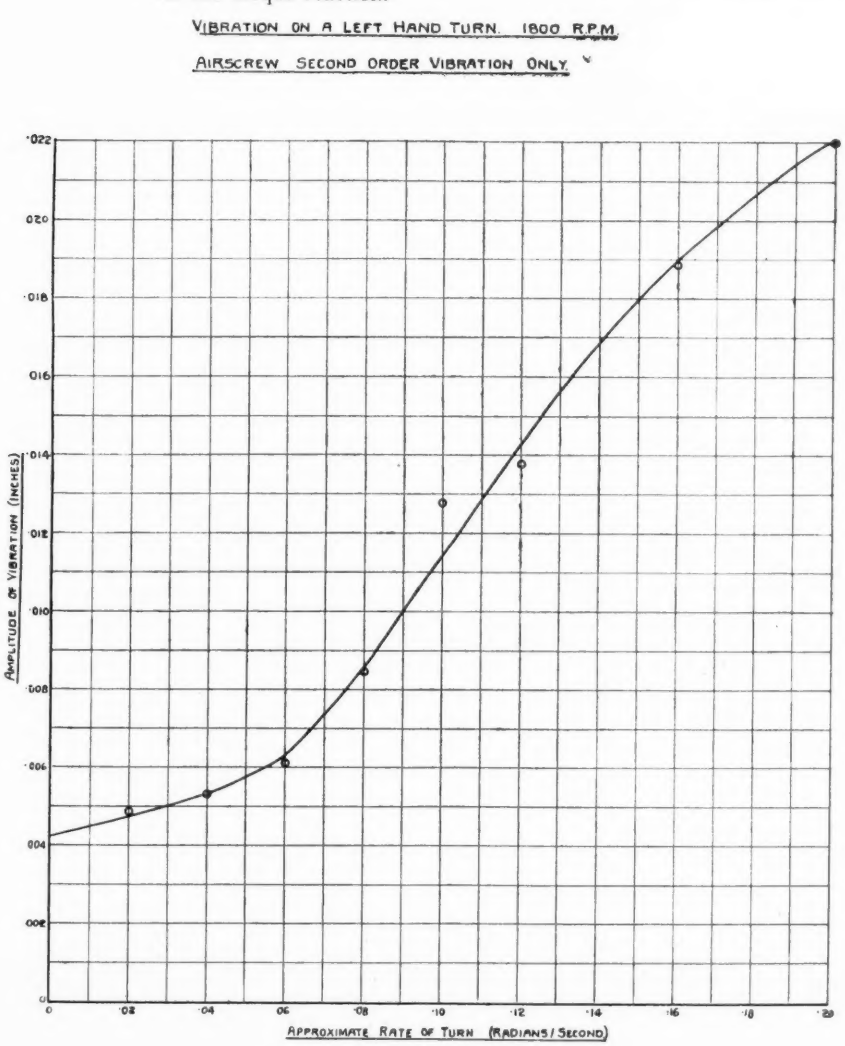


FIG. 23.

In a correctly executed banked turn source (2) is absent. In a supercharged engine source (4) is probably absent.

The aerodynamic couple due to incidence of the airscrew axis acts about a line perpendicular to the axis of rotation and rotating at twice airscrew speed, in the same sense as the airscrew. It may thus be represented by a rotating vector. The gyroscopic couple is similar and may be represented by a second vector rotating in the same sense as the airscrew. The aerodynamic vector is referred to axes fixed in the aircraft, whereas the gyroscopic vector is referred to axes fixed in space—for a level turn without losing height. Consequently, as the angle of bank of a turn increases, so the phase angle between the two vectors alters. This alteration in phase must be taken into account when combining the vectors to obtain the resultant couple on the aircraft. In addition to these sources of vibration there is the effect of disturbed engine carburation. Under the particular conditions obtaining on the flight tests where this vibration has been measured, disturbance of the carburation has manifested itself by engine spluttering and an increase in the first order harmonic of the engine torque reaction.

As the rate of turn is increased the gyroscopic couple increases and the aerodynamic couple also increases owing to the incidence of the aircraft and therefore of the airscrew axis increasing. Whether the resultant vibration increases or not depends upon the phase angle between the two components. No information is available concerning the effect of rate of turn on disturbance of carburation.

The effect of turn on the vibration of an aircraft with a geared supercharged radial engine is shown in Fig. 23. The conditions refer to a left hand turn at 1,800 r.p.m. The curve gives only the airscrew second order vibration, there being no change in the other components of the total vibration. The very large vibration shown is the effect of gyroscopic and aerodynamic couples totalling some 7,000lb. ins.

In other instances, however, very little increase of vibration has been observed. The investigation is proceeding and it is hoped that it will shortly be possible to clear up some discrepancies at present existing between observation and theory.

This completes our survey of the sources of vibration and of the effect of these sources on the vibration of the aircraft. We proceed now to the consideration of a number of specific problems.

Consideration of some Specific Problems

1 Comparison of Two and Four-Blade Airscrews

The results of vibrograph tests indicate that the effect of the substitution of a four-blade airscrew for one with two blades is a reduction in two types of vibration.

The first of these types is that of airscrew second order. We have already seen that in an airscrew with more than two blades the second order airscrew vibration, due both to aerodynamic and gyroscopic couples, is completely removed. The combined vibration of airscrew second order and engine first order occurring in a Bristol Fighter Falcon III fitted with a two and with a four-blade airscrew is shown in Fig. 24. It was not possible to separate the two sources of vibration in the analysis of the records, but the separation can be effected by a comparison of the two curves shown in the figure. The upper curve relates to the two-blade airscrew and shows the combined effect of the airscrew and engine vibrations, whereas the lower curve shows for the four-blade airscrew the vibration due to the first order harmonic of the engine torque reaction alone. The average reduction of vibration measured over the whole speed range is about 46 per cent. This indicates that in the vibration with the two-blade airscrew

fitted 46 per cent. was due to the airscrew and 54 per cent. to the engine torque reaction.

The second of the two types of vibration which are observed to be reduced is that corresponding in frequency to airscrew first order or engine half order—it being usually impossible to separate the two in geared engines. The reduction in this vibration effected in an aircraft with a geared radial engine is shown in Fig. 25. The cause of this reduction is not yet definitely known, but an explanation is suggested, based on the following argument.

In the forced vibration tests on the Atlas aircraft it was noted that the characteristics of the fuselage vibration were greatly altered by turning the airscrew from the horizontal to the vertical position. In particular it was noted that over the speed range 900-1,100 r.p.m. this change in the airscrew position resulted in a large reduction in the flexural vibration in a vertical plane. The change in airscrew position results in such a large increase in airscrew

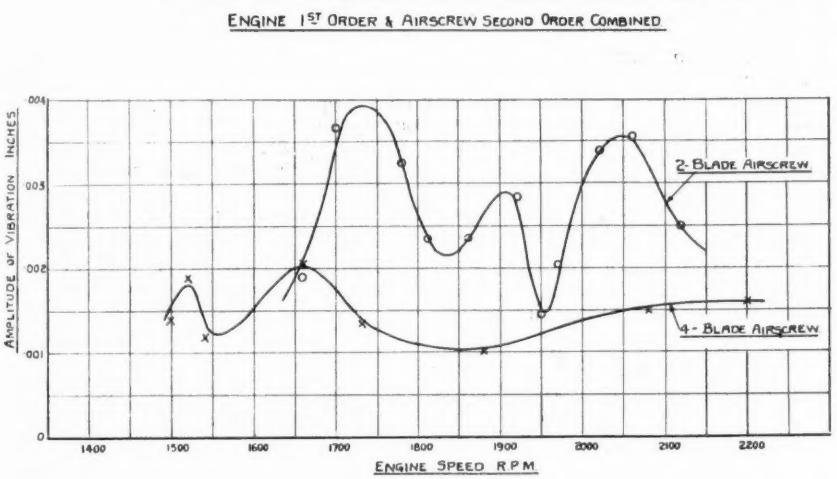


FIG. 24.

effective moment of inertia that a resulting change in vibration is only to be expected; the point of interest is that the change in vibration under the conditions specified, is a reduction. Now it is our general experience that the relative elasticity and distribution of mass in different aircraft are so similar that it is allowable to argue from one aircraft to another when discussing the general effect of changes of elasticity or mass. It appears, therefore, reasonable to suppose that for flexural vibration of an aircraft over a frequency range of the order of 900-1,100 r.p.m. a reduction of vibration will be effected by an increase in the effective airscrew moment of inertia for this particular type of vibration. In Fig. 25 the half order vibration we are considering has a frequency range of 800-1,100 per minute. With a two-blade airscrew fitted its effective moment of inertia is varying from a maximum to a minimum twice per airscrew revolution. With the four-blade airscrew there is no change in inertia, the value always corresponding to the maximum for the two-blader. The reduction in vibration when a four-blade airscrew is fitted is thus attributed to the increased effective inertia of the system at the airscrew. The effect is practically the same

as that described under " Interference of Airscrew and Engine." The argument has been presented here from a different aspect in the hope of making the matter clearer.

Speaking in general terms, the observed total reduction in vibration effected by the fitting of a four-blade airscrew is of the order of 30 per cent., but it of course varies for different orders of vibration and for different aircraft and engines.

2 *Comparison of Geared and Ungeared Engines*

Consider two engines, one ungeared and the other with a gear reduction ratio of 2 : 1, both running at the same speed and fitted with two-blade airscrews.

The engine vibration is the same for both engines. The vibration due to torque reaction is twice as great in the geared as in the ungeared engine. Although the increased diameter of the geared airscrew entails increased tolerances, these are more than offset by the reduction of speed and the net result is an average calculated reduction of 40 to 50 per cent. in the forces and couples due to airscrew static and dynamic unbalance. The couples due to airscrew out of pitch are substantially unaltered. The aerodynamic couples on the airscrew blades with the geared airscrew will be roughly double those with the ungeared. Gyroscopic couples on the turn will be slightly reduced with the geared airscrew. The change of airscrews thus involves an increase or decrease in the forcing couples, according to their source. Far more important than the mere halving or doubling of these couples is the reduction of their frequency towards the conditions of resonance. The shape of the resonance peaks shown in some of the figures gives an indication of the great amplification that may be imposed on the forcing impulses when near resonance.

It is apparent, therefore, that we should expect a large increase in vibration in a geared as compared with an ungeared engine, this increase being due in part to the increase in the harmonics of the torque reaction and the aerodynamic couples on the airscrew, but mainly to the lowering of the frequency of all the forcing impulses due to the airscrew.

3 *Stresses Imposed on the Structure*

In order to obtain an idea of the magnitude of the stresses induced in a fuselage as a result of vibration, a calculation was made into the stresses occurring in a certain fuselage as the result of a specified amount of vibration. For a given section of fuselage the stress induced is proportional to the amplitude of vibration and inversely proportional to the square of the distance between the two nearest nodes. In the case examined the amplitude of vibration was taken to be $4\frac{1}{2}$ thousandths of an inch and the distance between the nodes 12ft., corresponding to a three-node vibration. The greatest stress induced by a vibration of this character was found to have a range of 1.72 tons/inch^2 and occurred in one of the bracing wires.

The amount of vibration occurring in this example lies just on the limit of unpleasantness, so we are considering the stressing effect of the maximum allowable vibration without the occurrence of unpleasant physiological effects. The calculation referred to a single harmonic acting in a vertical plane. In general the fuselage will be subjected to a similar vibration in the horizontal plane, giving a total stress of 2 to 3 tons per inch^2. In addition to this, there will be added stresses due to other flexural and torsional harmonics, but as these will not usually be in resonance, their contribution to the total stress should not be very great. We may expect, due to all causes, a maximum range of stress of some 4.00 tons/inch^2 due to the amount of vibration normally occurring in aircraft. This applies only to the rear fuselage. Higher stresses may occur in the engine mounting, but these have not been investigated.

As we have already pointed out, in certain instances very bad vibration may occur and the corresponding stresses induced may be very large. It has been estimated that the maximum stress due to vibration in the fuselage members of a certain aircraft when executing a rather fast turn has a range of at least 15 tons/inch^2. This is, however, a rather exceptional case. For normal manœuvres the stresses due to vibration are not, with present day standards of safety, of very great importance.

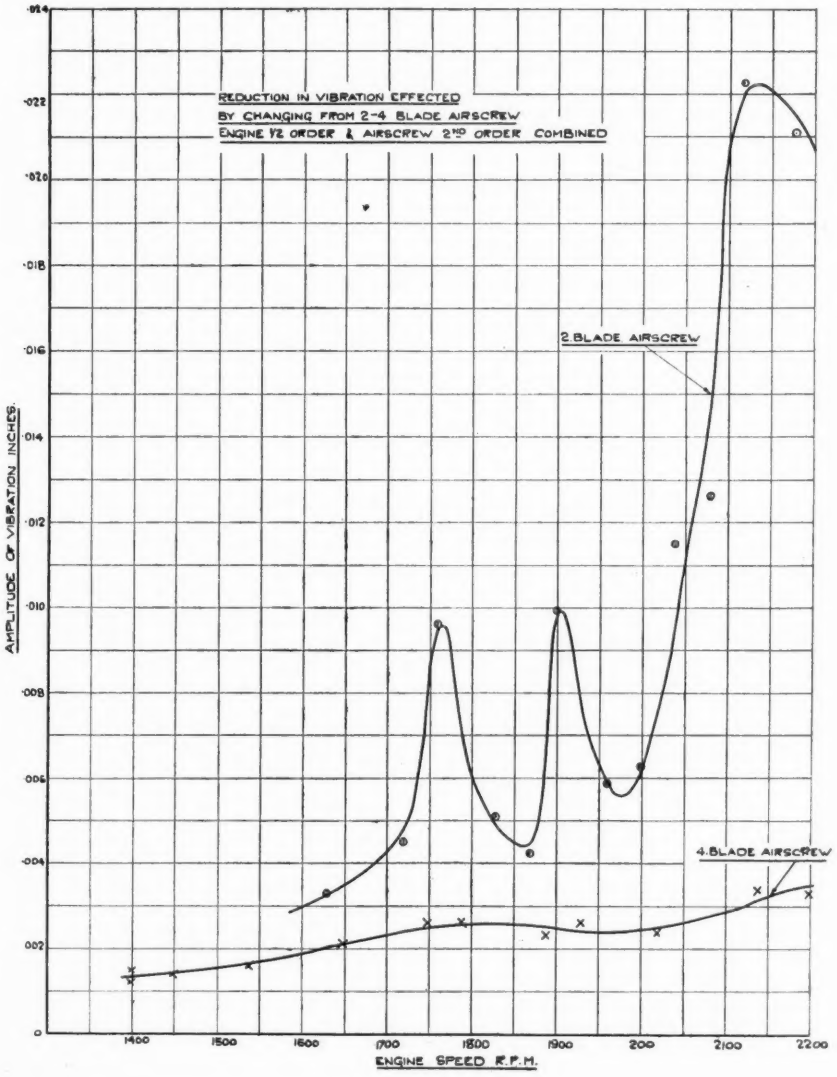


FIG. 25.

4 *Twin-Engined Aircraft*

The problem of vibration in a multi-engined aircraft is considerably more complicated than that in the single-engined type. It was therefore considered advisable for a start to confine our attention to the simpler case. In one instance, however, we have been able to obtain records of the vibration of a twin-engined aircraft, but their complexity is such that very little detailed information can be obtained for them. They are reproduced here simply as an indication of what may be expected to occur in the twin-engined type and as a further example of the relative effects of two and four-blade airscrews.

The results of the vibrograms which are shown in Figs. 26 and 27 give the vibration in a vertical plane of a longeron in the rear bomber's cockpit of an aircraft fitted with two geared radial engines. The results given in Fig. 26 were obtained with a two-blade airscrew fitted, and those in Fig. 27 with a four-blader fitted. Owing to slight changes in engine speed the relative phase of the vibrations from the two engines was continually altering, so that the amplitude of the resultant vibration was varying through a considerable range. The mean value of this range has in all instances been plotted. It will be seen that there are four different types of vibration.

(1) Engine torque reaction $\frac{1}{2}$ order or airscrew first order.
(2) Engine first order and airscrew second order.
(3) Engine second order.
(4) Engine high frequency.

The change from two to four-blade airscrews has practically no effect on the engine $\frac{1}{2}$ order vibration. This is to be expected since the airscrews are located so that they cannot affect the fuselage vibration by reason of any change in their effective moments of inertia. The combined engine first order and airscrew second order vibrations are reduced as usual, owing to the elimination of the vibration due to aerodynamic couples on the airscrew blades. The vibration of this type in Fig. 27 must be due entirely to sources in the engine. The engine second order vibration is very small in both instances, while the high frequency harmonics of the engine torque reaction are, as usual, negligible.

The Reduction of Vibration

The most effective method of reducing vibration is the reduction or complete removal of its source.

In ungeared, unsupercharged power-plants the engine is probably the cause of more serious vibration than is the airscrew. The introduction of gearing has had the effect of magnifying the airscrew's contribution to vibration, while supercharging of the engine has resulted in the decrease of a considerable part of the engine's vibration, probably due to improved distribution. As a result, the airscrew is now very frequently the chief source of bad vibration.

The most effective method of reducing airscrew vibration is the fitting of a three or four-blade airscrew. The result of this is the elimination of the vibration due to aerodynamic and gyroscopic couples, the chief source of vibration on the turn and in other manœuvres. If, in addition, the airscrew be dynamically balanced, the result should be an airscrew with practically no inherent tendency to cause vibration.

With regard to the engine, a reduction in vibration will follow on improvements in the balance, more particularly the secondary balance. The addition of a supercharger will improve the distribution and decrease the vibration due to torque reaction. The correct tuning of the carburettor, the supply of adequate heat to the air intake, carburettor and induction pipe, all serve to reduce the vibration caused by the harmonics of the engine torque reaction.

When all possible has been done to reduce the sources of vibration, a further improvement may be obtained by the insulation both of the sources and of in-

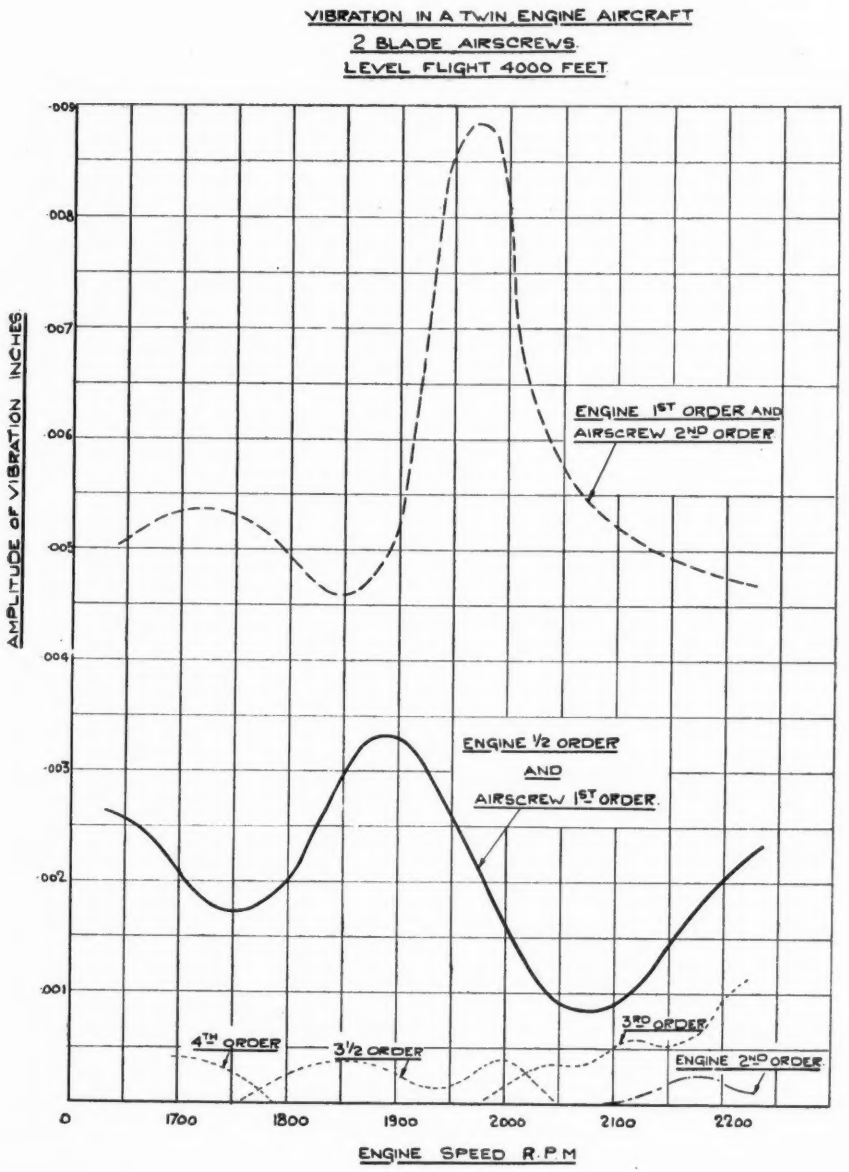

VIBRATION IN A TWIN ENGINE AIRCRAFT
2 BLADE AIRSCREWS.
LEVEL FLIGHT 4000 FEET
AMPLITUDE OF VIBRATION INCHES
·009
·008
·007
·006
·005
·004
·003
·002
·001
0
ENGINE 1ST ORDER AND AIRSCREW 2ND ORDER
ENGINE ½ ORDER AND AIRSCREW 1ST ORDER.
4TH ORDER
3½ ORDER
3RD ORDER
ENGINE 2ND ORDER
1700
1800
1900
2000
2100
2200
ENGINE SPEED R.P.M

FIG. 26.

dividual parts of the structure or fittings of the aircraft by the use of rubber or some other medium for absorbing vibration. It is also probable that the introduction of suitable vibration dampers would have a beneficial effect. A study of the effect of these is, however, beyond the scope of this paper.

Summary and Conclusions

We will conclude this survey of aircraft vibration with a brief summary of the main points that have been made. Starting with a study of the modes

Vibration in a twin-engined aircraft.
Four-blade airscrews.
Level flight 4,000 *feet.*

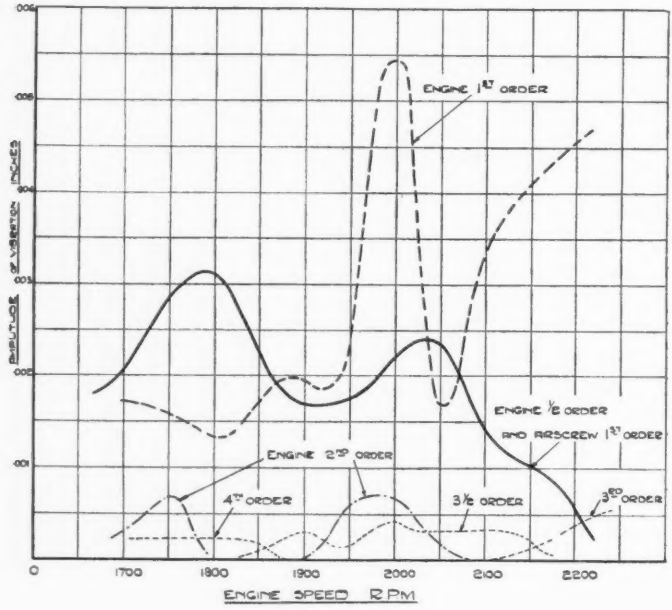


FIG. 27.

of vibration of a fuselage, we have shown how, for flexural vibration, the fuselage may have several modes of vibration in each of its two planes of vibration. When any source of vibration synchronises with the frequency of one of these modes, a resonant vibration is set up. Thus for flexural vibration in both the horizontal and the vertical planes there are several engine speeds at which resonance of some source of vibration occurs. The same state of affairs applies to the fuselage torsional vibration. Vibration of parts of the aircraft other than the fuselage has not been considered.

In order to obtain some idea of the magnitude of the forces and couples that might be applied to an aircraft without infringing some arbitrary limit of comfort, some tests were carried out on the physiological effect of vibration of different frequencies. As a result of these tests limiting values for the magnitudes of most sources of vibration were defined. These limits were found

to depend on the frequency of the vibration. Their lowest values occurred at a frequency between 1,000 and 1,400 per minute and limited the forcing impulses to 50lb. and 1,200lb. ins. for a force and couple respectively, in an aircraft of 4,000 to 5,000lb. total weight.

The actual sources of vibration existing in aircraft were then considered; the magnitudes of these sources were compared with the limits already laid down. As a result of this comparison it became possible to say which sources were the principal cause of unpleasant vibration. It was found that whereas the engine primary unbalance was insufficient to cause serious vibration, the engine secondary unbalance might do so when the specific unbalance was large. Of the harmonics of the engine torque reaction those of ½ order and first order were the only ones of importance. Normally neither of these were responsible for serious vibration, but either or both might be accentuated by a derangement of engine tune or by faulty distribution or ignition.

The chief source of airscrew vibration was the effect of cross-wind on the blades of the airscrew. When on the turn or when climbing with large incidence, this source of vibration might become very serious. Other sources of airscrew vibration were gyroscopic couples on the airscrew blades when turning, and airscrew static and dynamic unbalance under all conditions of flight.

During the consideration of a number of specific problems it was pointed out that vibration was greatly reduced as a result of replacing a two-blade by a four-blade airscrew and the reasons for this were discussed. The increased tendency of a geared engine to vibrate was attributed, not so much to the increase in magnitude of any of the sources of vibration, as to the lowering towards the conditions of resonance of the frequency of the forcing impulses due to the airscrew. The stresses imposed on the structure due to vibration were found to be usually small; but in cases where the vibration greatly exceeded the limits of unpleasantness the stresses might assume serious proportions.

In conclusion it is considered that by various means most instances of serious vibration can be cured, but the cost of this cure, whether in airscrew or engine efficiency may, in some instances, be greater than is justified by the increased comfort of the aircraft.

Discussion

The President: He was pleased to note that Mr. Constant had made some attempt, in his conclusions, to allocate the blame for the vibration experienced in aircraft. Usually the aircraft designer blamed the engine; the engine builder asserted that his engine would be all right if it were properly held down in a decent aircraft; and both of them blamed the propeller.

Mr. D. R. Pye (Deputy Director of Scientific Research, Air Ministry): The subject was one which had been forced upon their attention during the last few years largely owing to the development of the geared engine, and it was likely to become all the more important with the extended development of metal construction. There was a close analogy between the subjects of noise and vibration in aircraft—apart from the fact that noise was largely caused by vibration; each was a phenomenon of which everyone became unpleasantly aware and about which everyone held strong opinions, but yet, until quite recently, nobody had been able to state quantitatively what he regarded as an excessive noise or an excessive vibration. Mr. Constant, however, had made a real step forward in the disentangling of this very tangled skein and, so far as Mr. Pye was aware, this paper represented the first published account of any work of this kind.

Discussing some of the practical conclusions to be drawn from the paper, Mr. Pye expressed his satisfaction, as an engine man, in the fact that the airscrew had been called upon to bear some of the odium which so far had been inclined to rest entirely upon the engine, as the cause of excessive vibration. It was particularly interesting to learn that the accepted manufacturing tolerances in

airscrews were sufficient, under some circumstances, to cause excessive vibration to occur, according to the somewhat arbitrary scale which Mr. Constant had laid down. Again, the degree to which the four-blade airscrew must necessarily be more satisfactory than the two-blader from the point of view of vibration was a matter which had not been brought out and analysed so clearly before, so far as he was aware. It had been known generally that the two-blader was sometimes " rougher " than the four-blader, but Mr. Constant's paper gave the reasons for that, and a quantitative measure of the degree of smoothness which could be achieved.

A point of great interest with regard to the engine was that in a multi-cylinder engine a uniformly lower mean effective pressure in any one cylinder could very much exaggerate the half order or first order harmonic of the torque of the whole engine; that the half or the first order harmonics, which were the important ones, could be increased by as much as 50 per cent. through one cylinder giving a mean torque consistently 10 per cent. lower than the average of the rest.

Another important point in connection with radial engines was that the effective timing of the ignition could vary as much as from 38° to 46° before the dead centre, due simply to the articulated connecting rods. If the timing of the ignition in different cylinders could vary from 38° to 46° before the dead centre, it was inevitable, or at least very probable, that the mean torque provided by the cylinders would be different. There would arise, therefore, the condition which favoured the production of the half order harmonic—the serious form of forcing impulse. It should be possible to improve this state of things by an equalisation of the ignition timing.

Perhaps it was not inappropriate to refer to another aspect of the rough engine. It was well known that the mean effective pressure in a cylinder was very little affected by the mixture strength, provided that mixture strength was well on the rich side of the complete combustion mixture; in other words, there was a strong incentive to have all the cylinders working with rich mixtures, in order to obtain uniform torque throughout the cylinders. Thus the incentive to economy and the incentive to smooth running were in direct opposition. He had felt for a long time that the major problem before the engine designer in these days—the weight having been reduced and the power increased to a phenomenal degree—was the improvement of the fuel economy of the engine under cruising conditions. That could be effected only if the uniformity of fuel distribution could be improved. Real fuel economy under cruising conditions could be obtained only if all the cylinders were working on a mixture which, if it had not less fuel than the complete combustion mixture, at least had no serious excess of fuel over the complete combustion mixture. But it would be impossible to reduce the specific fuel consumption over the whole engine by having all the cylinders working on an economical mixture, unless at the same time the fuel distribution to all the cylinders could be maintained exactly uniform. For otherwise one would inevitably be jumping out of the frying pan of uneconomic fuel consumption into the fire of excessive vibration; because when operating with an economical fuel-air mixture the power of each cylinder would be more sensitive to the exact fuel-air ratio it was receiving.

It appeared that Mr. Constant had based his criteria as to what was allowable vibration entirely upon physiological considerations, although he had also referred to high-frequency vibrations which were physiologically less unpleasant. On one of the diagrams exhibited there had been a dotted curve, very low down, showing only very small amplitudes of vibration, but representing a high-frequency, and Mr. Pye asked for expressions of opinion as to the effects of those high-frequency vibrations upon the structure of the aeroplane. It had been made clear, by the early physiological experiments, that the vibrations which were unpleasant to the occupants of the aircraft were the low-frequency vibrations, but it seemed that we ought, perhaps, to consider the problems of vibration in two categories—the low-frequency vibrations, from the occupants' point of view, and vibrations of a quite

different order, and of much higher frequency, from the point of view of the aircraft structure; more particularly, perhaps, in connection with structures in which the welded type of joint was used.

In many of the diagrams, where the horizontal scale represented engine revolutions, and where Mr. Constant had shown, for example, the effect of the half order forcing impulse due to the engine, a series of vibration peaks were shown corresponding to certain engine speeds. Mr. Pye asked with what accuracy the actual frequency of the measured vibration corresponded with a simple fraction or multiple of the engine speed at which the peak was shown. For example, if one were measuring what Mr. Constant had called the half order engine vibration, when the engine speed was 1600, was the vibration frequency exactly 800, or how closely did the noticeable vibration correspond with the engine speed?

Major B. C. CARTER (R.A.E.): Mr. Constant had presented a picture of aircraft as musical instruments in the sense that one felt rather than heard the noise. The instrument would play tunes in the horizontal plane, the vertical plane, and torsionally, and apparently the engine and the airscrew were the two main producers of the tunes. Prior to the investigations described in the paper, there was no precise knowledge of the amplitude or frequency of the vibrations to be measured, so that to acquire the ability to measure them constituted quite a great step; it was hardly hoped that it would be possible to analyse the vibrations to the extent that Mr. Constant had analysed them, and to attribute the various vibrations to their exact causes. Mr. Constant had had to work with such aircraft as were available while being used for other investigations and, in general, it was not possible to get comparative records showing the changes brought about by altering one variable at a time. He was all the more to be congratulated, therefore, on his success.

With regard to Fig. 12, showing the harmonics in the torque curve of a 9-cylinder radial engine, Major Carter said he did not think Mr. Constant could be right in stating that the dotted curve corresponded to the theoretical vibration of the various orders in the absence of articulation. The fact that there were any orders of vibration below the $4\frac{1}{2}$ order must mean that articulated rod effects were taken into account in determining that curve.

Another point of interest was that of insulating the engine from the aeroplane as regards vibration. No work had been done on that problem at Farnborough, but, from the unbalance figures given in the paper, it was possible to ascertain quite quickly how much the engine would move in space if there were no restraint in the mounting. The translational movements varied from 1.5 to 1.8 thousandths of an inch for primary unbalance (*i.e.*, if there were no restraint in the mountings and the engines were allowed to vibrate in space) whatever the speed of rotation. That really meant that the resiliency of the mounting could be arranged fairly easily to allow the engine to move enough to prevent an important portion of the unbalance forces coming on to the mounting; that small movement would not alter the compression in the springs or buffers very much. The secondary unbalance figures were larger, ranging from 2 to 3.6 thousandths of an inch. The unbalance couples also produced angular movement of the engine in space, independently of the speed of rotation. Those movements could be expressed in millionths of a radian, and they ranged up to 30 millionths for primary unbalance and 47 millionths for secondary unbalance.

Communicated.—If S_t denote specific unbalance for forces (pounds force/pounds weight) corresponding to an unbalance frequency F per minute, the amplitude of free translational movement is A inch where:—

$$A = 35000\, S_t/F^2.$$

Again, if S_a denote specific unbalance for couples (pounds inches/pounds inches squared), the amplitude of free angular movement is β radian, where:—

$$\beta = 35000\, S_a/F^2.$$

Both S_t and S_a are proportional to F^2 and thus A and β are constants for primary unbalance and (different) constants for secondary unbalance. Values corresponding to the quantities given in Table I may be computed from the above formulæ.

If R denote the crank radius in inches, the quantity A/R represents the amplitude of free translational movement as a proportion of the crank radius and is a non-dimensional index of translational unbalance in relation to engine size and weight.

The amount of linear movement associated with β over a length (R) say, is proportional to R, so that β is an index of angular unbalance in relation to engine size and weight.

Both A/R and β have the merit of being independent of engine speed, so that they are inherent features of the engine design. The values of S_t and S_a may be derived from them for any engine speed when the crank radius is known. In this connection it is to be noted that, to be comparative, specific unbalance values must be computed with the same convention as regards units. For simplicity, the engine alone has been considered in the foregoing, whereas airscrew inertia requires to be taken into account when considering an engine on its mounting.

Captain J. MORRIS: He felt that many of the conclusions arrived at in the paper would have to be considered very carefully before they could be accepted. The instrument used appeared to be rather unreliable, and Captain Morris recalled some early experiments, the results of which had illustrated the importance of using reliable instruments. During the war the Royal Aircraft Factory had set up a spinning gear for the testing of propellers, and found that a certain type of propeller failed invariably when tested on this gear, whereas another type of propeller was uniformly successful when so tested. It so happened, however, that the type of propeller which failed on test had in fact given very good service in France, and no complaints were made about its behaviour in practice, whereas the type of propeller which had always behaved well on the test gear gave very bad results in practice. He believed the trouble was found to be that the test gear with the type of propeller which proved reliable in practice had a resonant period at the testing speed, so that the fault lay with the testing gear and not with the propeller.

The two-bladed propeller had come in for a certain amount of condemnation, and rightly so. He understood that two-bladed propellers were more aerodynamically efficient than three or four-bladed propellers, and that they were easier to make. Also, they were easier to transport. But they had various disadvantages.

Dealing first with periodic gyroscopic torque, discussed by Mr. Constant, he said that this would occur only if the aircraft were turning uniformly. If the aircraft were not turning uniformly—and very rarely would it turn uniformly for any length of time—that torque was rather arbitrary and was not a steadily-applied forced vibration; but it might well be that, when turning at certain speeds, there were very severe strains on the propeller shaft. It seemed to him that the two-bladed propeller behaved most extraordinarily from the point of view of vibration. In a certain speed range it was absolutely impossible for a two-bladed propeller to vibrate. There was first the lower whirling speed, and later there was an upper whirling speed, both of which arose from lack of balance; between those two speeds the propeller, even if it were perfectly balanced, could not vibrate, but apparently would smash up. Some years ago, with the backing of Colonel Fell, he had suggested certain experiments to the Air Ministry, with a view to verifying this theory, but the work was considered academic and nothing was done about it. He still believed, however, that this matter was very important and should be studied. It seemed that the gyroscopic effect of a two-bladed propeller affected the apparent elasticity of the propeller shaft until a range of

speed was reached at which the whole of the elasticity had gone. Above that range the apparent elasticity was restored.

With regard to torque, he did not wish to be dogmatic, but he had always thought that if the cylinders were more or less equal and the working conditions equal, from the torque point of view, the fundamental, whose speed was half that of the crankshaft, and all the harmonics up to the number of cylinders of a single throw radial, would balance out, and one simply started off, in the case of the 9-cylinder radial engine, for instance, at the 9th harmonic. He was surprised to read in the paper—and apparently Major Carter supported the view—that this fundamental had become important. The matter seemed to be one entirely for engine designers.

Mr. W. O. MANNING (Fellow) : He would like to draw attention to airscrew vibration caused by the blades of an airscrew coming near to some part of the structure of a machine in the course of their travel. In the old F-boat type the propeller was very close in front of the biplane cellule. The propeller centre was about half-way between the two planes; the space between the planes was about 8ft., and the diameter of the propeller was about 9ft. 6in., so that the propeller blades slightly overlapped the planes. When a two-blade propeller was fitted to that machine the vibration was so great that it was impossible to run the engine up on the ground, but when the usual four-blade propeller was used the vibration was normal. Certain types of monoplanes, with engines fitted very close to the wing, were becoming popular; and possibly, therefore, the type of vibration to which he referred might be more often met with in the future. Three-blade propellers might become more popular in the future, as the use of metal for propellers extended. He understood that vibration troubles were likely to be much less serious with a three-blade propeller than with a two-blade propeller, and he asked if Mr. Constant could say what improvement might be effected by the use of the three-blade propeller.

Enlarging upon Mr. Pye's remarks, he said there was very considerable divergence between French and English practice in connection with carburation in aero engines. Nearly all the English engines depended on two carburettors, but it seemed to be the modern French practice to fit six on a twelve-cylinder engine; the later the French engine, the more carburettors it seemed to have. There was little doubt that the object of that practice was to secure good carburation right through the engine, with consequent avoidance of roughness, and also to ensure economy by being able to use the best possible mixtures without being troubled by distribution problems.

Mr. FEDDEN (Bristol Aeroplane Co.) : It was shown by Fig. 8 that the limit of unpleasant vibration was only slightly dependent upon the speed when the frequency exceeded 2,000 per minute. From this it should follow that the permissible magnitude of an out-of-balance force or couple should increase as the square of the frequency, provided the mass or moment of inertia were kept constant.

It was obviously impossible to adhere to the limits of 50lbs. and 1,150lbs./inch given in the paper, and these limits must depend on the frequency. He asked if there was any reason for the difference in the laws governing the variation of permissible forces and couples with frequency.

Mr. Fedden also asked if the couple mentioned in Fig. 10 was resultant or component, and whether there was any further information available for the extrapolation of the curves given.

In view of the statement that the dotted curve in Fig. 12 did not allow for the articulation effect, he asked if this were also the case in respect of the full curve, *i.e.*, had the articulation been taken into account in deriving the torque curve, apart from the effect embodied in the actual indicator cards?

Referring to the statement that an out-of-balance couple of 8,000lb. ins. in an airscrew was found to be unsafe, he asked at what speed this occurred.

The data given concerning the vibration set up by the battering effect of the slipstream furnished additional confirmation of the benefits to be derived from the use of three- and four-blade airscrews.

Mr. Fedden asked if any information was available as to the magnitude of the fluctuation effect at different speeds; *i.e.*, should the gear ratio of the airscrew be as near as possible to a simple fraction, or should it be considerably removed therefrom?

Discussing the section of the paper in which geared and ungeared engines were compared, he said it was obvious, from the statements made, that much of the vibration attributed in the past to geared engines was really inherent in the slow-running two-blade airscrew; hence, this was not really an engine fault.

Finally, he felt that Mr. Constant had made a great point when he had referred to distribution, and advances should be expected in this direction. It would appear that a direct fuel injection as against the injection of a carburetted gas mixture was a matter which could with advantage be explored.

Mr. M. L. BRAMSON (Fellow): One of the most striking things brought out by the paper and the discussion was the contrast between the general order of amplitudes referred to in the paper and those mentioned by Major Carter. If, as Major Carter had said, an engine suspended freely in space would have an amplitude of vibration—presumably at the engine bearers—of the order of only 1½ thousandths, or thereabouts, and if the amplitudes measured in the fuselage were frequently of the order of 6 thousandths or more, it seemed to follow that the increase of amplitude must be due to the greater or smaller degree to which resonance frequencies were approached. He asked if that was so. His principal question was to what extent could the problem of preventing unpleasant vibrations in the fuselage be dealt with by removing the natural periods of vibration of the fuselage as far as possible from the principal frequencies of the power plant or the propeller.

Commenting upon Major Carter's reference to an aircraft as a musical instrument in which one did not hear the music, he said he did not remember which was the lowest audible frequency, but he did know that vibration and noise frequencies overlapped very considerably, as could be demonstrated in a hall in which there was an organ producing low notes. Therefore, he asked whether the higher frequencies, secondary and so forth, reached audible frequencies, and whether in some cases, and if so to what extent, they reached the passengers in the aircraft in the form of noise.

Major CARTER: In reply to Mr. Bramson's remarks, in secondary vibration the amplitude might be as much as 3½ thousandths.

Mr. BRAMSON: Even so, it was lower than was referred to in the paper.

Major CARTER: It was amplified by resonance. His reference to the aircraft as a musical instrument was meant to convey that we were concerned, that evening, rather with what was felt than with what was heard; the Atlas aircraft made a most dreadful noise when vibrated as described in the paper.

Mr. E. J. FEARN (Associate Fellow): With reference to the primary "unbalance" forces for certain radial engines, as shown in Table I of the paper, in respect of the first three engines mentioned, the X and Y components were identical. That was a very interesting result, because for all the engines of this type that he had investigated these components were *unequal*, *i.e.*, the polar diagram of the out-of-balance force was not represented by a circle, but was of elliptical form; this "ellipse" being not quite symmetrical even for a symmetrical engine. However, this matter was more or less of academic interest only. What was more remarkable was that the engine makers had allowed this force to remain unbalanced. He asked Mr. Constant whether the primary out-of-balance results were obtained by an analytical method or by a practical test with a vibrograph, for he presumes that such a test could be made if the crankshaft were rotated

at a constant speed by an electric motor. If actual tests had proved the engine to be out-of-balance, then the engine makers ought to be informed, since, by the addition of a suitable mass, the greater part of the primary out-of-balance force can be eliminated. If the out-of-balance results were obtained by analysis, then he would like to know what method was employed; and if they were obtained by a bench test, then a description of the manner in which this test was carried out would be of considerable interest.

He considered that the analysis of a torque curve was a very dangerous procedure. One had only to consider the nature of the torque curve for a single-cylinder engine in order to appreciate its non-harmonic nature. The strokes of compression and expansion were so completely different from the strokes of suction and exhaust that, if for any reason a harmonic analysis be required, one would have to consider some 30 or 40 harmonics in order to obtain the primary harmonic with any degree of accuracy. He had noted that Mr. Constant analysed one cylinder at a time, but his (Mr. Fearn's) view was that, rather than add together the results of a number of single cylinders, a more accurate result is obtained by the analyis of the torque curve for the complete engine. He could not understand why the effect of the connecting rods' articulation should be omitted from the theoretical curve on Fig. 12, for, if it were included, the effect of faulty distribution, etc., could be evaluated. He understood that articulated rod effects were included in the full-line curve (plotted from actual indicator cards), but that they were omitted from the dotted curve (giving theoretical results). The comparison, therefore, was hardly fair.

In conclusion, Mr. Fearn said he disagreed with some of Mr. Constant's conclusions, but, inasmuch as he disagreed with some of the original assumptions, this was to be expected.

Mr. J. CARTER: In addition to the three types of vibration that had been mentioned—torsional, horizontal and vertical—reference should have been made to a fourth type, *i.e.*, longitudinal vibration. Why should they imagine that there ought to be longitudinal vibration? In this connection he mentioned a recent occasion on which an engine had broken a bolt head, which had proved to him that in an engine of that description there was some overload force on a main bearing which caused a longitudinal vibration in the engine, which might have carried the effect of another harmonic through the whole machine, and which might have altered the whole of the curves. Mr. Carter also recalled a statement made recently by a lecturer at a meeting of the Society, to the effect that there was very little left for engineers to do towards the betterment of aircraft. His own opinion, however, was that the time was never more ripe than at present for effecting improvements. They had reached a stage at which vibration had become very serious, not only from the point of view of the passengers, but also from the point of view of the machine. According to the figures in the paper, there was nearly two tons throwing about spare and uncontrolled in engines. If that were so, then they must expect vibration, and they must look for a means of controlling it. The graphs shown in the paper indicated apparently that the lower the engine speed the greater was the vibration. That suggested higher engine speeds, which meant smaller cylinders, and it also meant that if they were to maintain the same horse-powers they must have more cylinders, and that, in turn, meant greater weight. They must not expect an engine to tick over at a speed of 400 r.p.m., and to be ideal throughout the range from 400 to, say, 2,200 r.p.m. He contended that engines, instead of being throttled down to tick over at 400, should be designed to tick over at the normal revs., so that, as the engine was opened up, the revs. would never alter; that was possible and practicable. If they could balance an engine at definite set revs.—and Mr. Constant had said that it could be done—they could reduce the vibration to the minimum.

Mr. CAPON (Fellow): Whilst it was true that, as the President had stated, Mr. Constant had been engaged on torsional vibration problems for three or four years, he had not been specialising on aircraft and engine vibration in general for more than about a year, and it was wonderful that in such a short time he should have completed the whole of the work described in the paper. Just before that work was commenced, a conference had been held at the R.A.E. on the subject of vibration, and it was interesting to note that one of the conclusions arrived at then had been completely altered as the result of Mr. Constant's work. At the time of the conference they had been very much impressed by the great amount of vibration which appeared to occur in geared-engined aircraft, and had assumed that it was due to the torque fluctuations, whose effect, as the lecturer had pointed out, was increased in proportion to the gear ratio. It had appeared since, however, that the airscrew was probably the principal offender, and that the engine torque fluctuations were of less importance. It was now realised that the increased vibration when the engine was geared was not due to any increase in the forcing couples and forces, but to the approach of the periods of these couples and forces to the lower free periods of vibration of the aircraft.

Mr. A. C. LOVESEY (Rolls-Royce, Ltd.): He would like to refer to the particular type of vibration which arose when a machine was making a turn. In the case of a particular machine having a 12-cylinder engine, with a reduction gear, and using a two-bladed metal airscrew, a rather severe vibration occurred when making left-hand turns with the engine running at 1,400 r.p.m. The airscrew was turning at 750 r.p.m. Strangely enough, however, the engine appeared very much smoother when making right-hand turns at this speed than when in straight flight. He rather associated this with the variation of gyroscopic torque, and was probably a case in which a cure could be effected by using a three-bladed airscrew.

Probably one of the greatest offenders in respect of vibration was faulty distribution which became particularly evident at very low air temperatures. It was sometimes said that supercharging helped distribution, but his own experience had been that it was more difficult to get good cold distribution with supercharged than with naturally aspirated engines.

REPLY TO DISCUSSION

I am very interested to hear that Mr. Pye considers that a variation in ignition advance of 8° between the different cylinders would favour the production of the half order harmonic. I must admit that I am myself not completely convinced that the effect will be serious unless the engine is running on a very weak mixture or the conditions are so unfavourable that the cylinder with the greatest advance is caused to detonate. I have been unable to obtain reliable figures connecting ignition advance with the mean torque given by a single cylinder at constant speed.

There does not appear to be any reason to suppose that the high frequency vibrations have a more serious effect on the structure of an aircraft than do the low frequency vibrations. If the stress in the structure or fittings of an aircraft due to steady vibration is sufficient to cause fatigue failure, that failure will occur at a comparatively early stage in the life of the aircraft. The stress occurring is determined more by the amplitude of movement than by the frequency of the forcing impulse. It would appear that the frequency most harmful to the structure or fittings is that which will cause the part in question to resonate. Experience has shown that those members which are particularly liable to failure usually resonate at fairly low frequencies in sympathy with comparatively large forcing impulses.

In reply to Mr. Pye's query as to the accuracy of frequency measurement with the Cambridge Vibrograph, it has been found that in general there is no more than 20 periods per minute difference between the frequency of the recorded vibration and the frequency of the forcing impulses as determined from the engine speed indicator.

From the remarks of Major Carter and others, there appears to have been some misunderstanding as to the method of taking articulation into account in building up harmonic torque curves. The theoretical and actual torque curves analysed in Fig. 12 were obtained by the following processes. To obtain the theoretical torque curve the same indicator card was used for each of the nine cylinders. Owing to the presence of articulation, this indicator card gave rise to different single cylinder torque curves in the different cylinders. These nine torque curves were combined to give the resultant for the complete engine. Articulation was therefore taken into account in forming the torque curves from the given indicator card. But its effect in causing a variation in the indicator cards of the different cylinders due to a varying ignition advance was not taken into account. The actual torque curve (shown by a full line in Fig. 12) was built up from actual indicator cards taken from the different cylinders of the engine and of course takes all these effects into account. The difference between the two torque curves is thus due to a small extent to the effect of articulation in varying, through the magneto advance, the indicator cards of the different cylinders. But to a much larger extent, this difference is due to the differences between the different cylinders due to faulty distribution, cylinder head leakage, etc.

Major Carter's figures for the free movement of an engine when unrestrained by its mounting are very interesting. I think that the amplitudes of free translational and rotational movement A and β probably provide a better means of comparing the inherent tendency of an engine to vibrate than do the figures for specific unbalance given in Table I.

The point of the reference of Captain Morris to the Royal Aircraft Factory spinning gear appears to be that an instrument is unreliable if it has a natural frequency close to the frequency which it is being used to measure. That point is perfectly appreciated, and has been borne in mind when analysing the records obtained. Most instruments have some limit to the range of their applicability, and to condemn an instrument because it is not of universal application seems rather impracticable. When measuring frequencies above 1,000 per minute, the Cambridge Vibrograph has proved in service to be extremely accurate and perfectly reliable.

With two-blade airscrews, the periodic gyroscopic couples occur when the aircraft is turning with uniform angular velocity. Any change in angular velocity, if it is to affect the periodicity of the gyroscopic couples, must occur at a rate comparable with that periodicity. In practice the inertia of an aircraft is such that changes of angular velocity are slow compared with the frequency of the gyroscopic couples. These couples may therefore be treated as being truly periodic.

Captain Morris points out that an airscrew will smash up if it is run just above its lower whirling speed. This is apparently ground for assuming that the lower whirling speed is above the speed range of airscrews as used to-day.

Captain Morris is correct in his impression that all the minor harmonics in the torque reaction would cancel out if the working conditions for all the cylinders are equal. Unfortunately they are, in practice, not equal.

In reply to Mr. Manning, I have not yet met a case of vibration being caused by interference between the airscrew and the aircraft structure, but there is no doubt that such vibration will occur if the tip of the airscrew blade passes close to any part of the structure. In such a case the fitting of a four-blade airscrew should simply double the frequency of the forcing impulses. The reduction in

the amplitude of the vibration mentioned by Mr. Manning, may in parts be attributed to this doubling of the frequency, but it is more probably accounted for by the elimination of the vibration due to the aerodynamic couples which are always associated with a two-blade airscrew. Three or four-blade airscrews with equally spaced blades are equally effective in reducing vibration. With both types the forcing impulses due to gyroscopic and aerodynamic couples are non-existent.

I consider that the multiplication of carburettors should result in better distribution and therefore a more uniform torque curve. The complications involved in the use of a large number of carburettors may, however, be so serious as to make their use impracticable without making sacrifices in other directions.

I regret that I can give Mr. Fedden no further information for the extrapolation of the curves in Fig. 10. The forces and couples given in this figure are components. If there are two equal sources of vibration then the maximum permissible value for each component will be only half that given in the figure. It usually occurs, however, that at any particular speed there is no more than one vibration in resonance at a time. The variation with speed of the maximum permissible force or couple depends not only on the variation of the maximum allowable amplitude as given in Fig. 8, but also on the variation of the effect of a given forcing impulse as given in Fig. 9. It is therefore not correct to say that the more permissible magnitude of out of balance force or couple should increase as the square of the frequency. Actually it appears that the maximum permissible force increases more rapidly and the maximum allowable couple less rapidly than would be expected on the basis of the square law. The difference between the laws governing the force and couple is due to the variation with speed of the position of the node nearest the point of application of the forcing impulses. The variation in the position of this node has a large effect on the relative importance of a force or couple, for whereas a couple is more effective at a node, a force will have the greatest effect when applied at an antinode.

The limits of 50lb. and 1,150lb./ins. were only given as an absolute limit of the maximum allowable force and couple. If this limit were not exceeded at any speed, no serious vibration would occur. If the limit were exceeded the vibration might or might not be serious according to the closeness of its frequency to the critical value of 1,500 per minute.

Tht out of balance couple of 8,000lb./inches referred to in the paper occurred at an airscrew speed of 1,870 r.p.m.

With a gear reduction ratio of exactly 2 : 1 there is no fluctuation in the amplitude of vibration due to airscrew engine interference. As the reduction ratio is increased or decreased from this value a fluctuation of fixed amplitude and increasing frequency occurs. I have no information as to what frequency of fluctuation is least unpleasant.

If the mechanical difficulties can be overcome, the direct injection of fuel into the cylinders should result in better distribution, a more uniform torque curve and consequently greater freedom from vibration.

I agree with Mr. Bramson that if there occur large fuselage movements compared with small movements of the engine when free in space, these large movements are due to resonance of the fuselage. There is, however, no evidence that any such magnification occurs. For example, the figures mentioned by Major Carter for engine secondary unbalance forces show that the engine, if free in space, would move with an amplitude of from 2.0 to 3.6 thousandths of an inch according to the amount of unbalance. With these same engines fitted the corresponding maximum movements of the fuselage are 2.1 to 3.2 thousandths of an inch (see Figs. 7 and 22). The figure of 6 thousandths of an inch which was mentioned would almost certainly be caused by a couple so that a direct comparison of engine and fuselage movement is not possible. It is possible to reduce

the amount of vibration very considerably by removing the more important natural frequencies of the fuselage as far as possible from the principal forcing frequencies of the engine and airscrew. This may be done either by lowering the natural frequencies of the system by the use of a flexible engine mounting, or by the raising of the frequency of the forcing impulses by using either a high speed engine or an ungeared airscrew.

The lowest audible frequency is of the order of 2,000 per minute. Vibrations of the structure of an aircraft of frequencies up to 8,000 per minute have been measured. It is clear, therefore, that the notes emitted by some of the vibrations of an aircraft have audible frequencies. It is, however, improbable that the intensity of the sound produced is sufficient to be heard, even if all other sources of sound were removed. Apart from the structure of the aircraft, sounds of considerable intensity are produced by drumming of the fabric of the wings and fuselage, by rattling and drumming of fairings, by creaking of joints and by cockling of the petrol tank.

The existence of primary unbalance in single bank radial engines, referred to by Mr. Fearn, is due to the effect of the articulated rod system. The relative values of the X and Y components depend upon the magnitude of the balance weights adopted. In the absence of detailed information as to the magnitudes used by the different firms, it was considered that the most reasonable basis of comparison was that based on the assumption that the largest unbalance component had been reduced to the smallest possible value, that is, that the two components were equal. The fitting of a balance weight provides a force which can be represented by a vector rotating at engine speed in the same direction as the engine. The residual primary unbalance in a radial engine may be represented by a vector rotating at engine speed in the opposite direction to the engine. This unbalance force cannot, therefore, be neutralised by an increase in the magnitude of the balance weights. The only means of neutralising it would be by the fitting of an out-of-balance weight geared to rotate in the opposite direction to the engine. The figures given in Table I were obtained by the usual method of analysis used for the calculation of unbalance in multi-cylinder engines.

I cannot understand Mr. Fearn's statement that to obtain by an harmonic analysis the primary harmonic of a torque curve with any degree of accuracy it is necessary to consider some 30 or 40 harmonics. By an ordinary Fourier analysis any required harmonic may be obtained without reference to any of the other harmonics. The analysis summarised in Fig. 12 was made on each of the single cylinder curves, instead of on the curve for the complete engine, in order that the effect of changes in the torque curves of individual cylinders might more easily be investigated.

It is difficult to see how a longitudinal vibration can take place in a single-engined aircraft, even if there were a source of longitudinal forcing impulses.

Mr. Capon has summarised very clearly the reason for the increase of vibration resulting from the introduction of reduction gearing. It would appear that any further reduction in airscrew speed by gearing would only be made tolerable from the vibration viewpoint by the fitting of dynamically-balanced multi-blade airscrews.

I consider that in the case referred to by Mr. Lovesey the vibration was caused mainly by the aerodynamic couples on the airscrew blades. On the turn gyroscopic couples will also arise and the resultant couple will depend on the phase angle between the two components. The vibration experienced would be eliminated by the use of a three- or four-blade airscrew.

I am very surprised to hear that Mr. Lovesey considered cold distribution to be worse on supercharged than on unsupercharged engines. Given the same atmospheric conditions, one would suppose that the temperature rise imparted

to the mixture by the supercharger would result in better distribution in the supercharged than in the unsupercharged engine. If distribution troubles occur in a properly tuned supercharged engine I am of the opinion that these troubles would be present to a much larger extent in an unsupercharged engine operating under the same atmospheric conditions and subject to the same conditions of induction pipe heating.

In conclusion, I should like to express my appreciation of the advice and assistance afforded me in the preparation of this paper by Major Carter, of the Royal Aircraft Establishment.

THE EFFECT OF ACCELERATIONS ON HUMAN BEINGS

BY

J. L. NAYLER

The amount of information on the effect of accelerations on human beings is scanty and somewhat rudimentary with the single exception of observations made on aeroplanes. Aircraft in general have to be built to certain factors of safety so as to keep the total flying weight as small as possible, and for this reason accelerometers have been carried to measure the resultant forces experienced in flight. In this way a measure has been obtained of the forces likewise impressed on the human pilot directing the craft. The practice of flying has gradually developed by the careful training of the pilots so that undue stress is not placed on the aircraft structure and as a corollary this has been made possible by the pilot using his physical sensations to limit the violence of any aerobatic manœuvre. But the practice in this respect differs in various countries and so an attempt is here made to collate what information exists on the effect of accelerations on the human body and to consider whether the stresses experienced in flight can be increased with safety. It is, however, realised that the subject is a very open one and that the experimental data are very scanty.

Let us first take an apparently inexplicable occurrence. In September, 1931, a man fell on to a heap of ballast from a height of 50 feet, at the site where the Hotel Cecil once stood. Much against his will he was taken to hospital and the doctors could find nothing wrong with him. He walked home unaided. Many have expressed great surprise that he was not killed or at the least severely injured. Further consideration will show that this escape from injury was not perhaps abnormal.

In discussing cases such as the above it is easiest to put down the figures in the manner adopted and standardised by the aerodynamist. All objects on the earth are subjected to the force of gravity and this force is spoken of as that due to the acceleration "g." of gravity. The figure 1g. implies then that acceleration caused by the ordinary gravity forces is roughly 32 feet per second per second. The actual force on a body (or its weight) is the mass of the body multiplied by 1g. If the acceleration be doubled, then the force (or weight) is doubled although the mass of the body experiencing the acceleration remains the same. To measure this acceleration instruments have been designed which are called accelerometers, and the accelerometer reading is 1g. when the instrument is at rest and set to read in a vertical direction. Any additional vertical acceleration is, therefore, additive to the normal 1g., which has to be subtracted from the accelerometer reading to find its true value.

Accelerometers have been much used in aircraft so that figures for flying manœuvres are known by direct measurement and will first be quoted. Other figures have to be calculated from recorded performances and feats. These last tend to show that the human body has still something in hand compared with the accelerations normally experienced by pilots flying aeroplanes.

Judging from the results of experiments published in this country and in U.S.A., the average pilot seems to suffer no discomfort during ordinary manœuvres on an aeroplane and no doubt his training has helped him to limit the strain on his aeroplane which is usually not stressed in Great Britain as regards design strength for more than nine times the force experienced in normal horizontal

flight. The maximum accelerometer readings on a single-seater aircraft (R. & M. 1932), which are in some cases only experienced for a small fraction of a second, are roughly

$2\frac{1}{2}$-4g. during pulling out of a dive
$2\frac{1}{2}$-$3\frac{1}{2}$g. during a flick roll or a normal loop
2-$4\frac{1}{2}$g. during a rocket loop
2-4g. during a turn.

It is also known that during a continuous spin the acceleration may be 2-3g. for many seconds. In upside down flying the reading is normally not less than −1g., giving a total acceleration downwards of 2g. These figures may be considered as normal practice and suggest that they leave a factor of safety on the aircraft of 2 under all normal flying conditions.

More abnormal conditions have been experienced without ill effect to the pilot. Individual records of pull-outs from a dive have registered accelerometer readings up to 6g. without pilots experiencing any ill effects. This is a transient acceleration. On the other hand, some Schneider Trophy and other high speed pilots have stated that on a continuous turn at high speed they see "black" although their muscular sense remains, and calculation shows that the accelerometer reading will remain as high as $4\frac{1}{2}$-5g. for several seconds. An equal acceleration for a shorter period of about two seconds with a peak value of, say, 6 gives little or no discomfort. Furthermore, a few pilots of exceptional physique make at least as steep turns and apparently experience no blacking out.

If we turn to American practice we find that their pilots experience as high or higher accelerations. As regards a long continued acceleration their experience agrees with ours; Lieut. J. H. Doolittle, in the U.S. Report N.A.C.A. No. 203, suggests that accelerations of the order of 4.5g. continued for any length of time result in a complete loss of faculties, and he reports 4.7g. on a bank of 70° at 140 m.p.h. and 5.3g. for 75° bank at the same speed. It is believed that this pilot is one of the first to try out his physique in this way.

In the inverted position discomfort seems to be the predominating factor. The accelerometer reading does not normally exceed −1g., which implies a force equal to twice the normal weight. Lieut. Williams, of the United States Navy, in *Aero Digest*, speaks of negative accelerometer readings of −4g. in an inverted loop (bunt) which implies a force of five time gravity. Whether the human body can accommodate for negative accelerations as well as it can for those of normal sign remains to be discovered, but Lieut. Williams believes that such will not be found to be the case.

Another American paper, N.A.C.A. Report No. 307, states that an acceleration of 10.5g. was recorded in one manœuvre in which the pilot suffered severely and adds that the limits of physical resistance of the pilot to violent manœuvres are being approached. It is understood that he was reported fit after two months' rest. Since the date of this paper (July 9th, 1928), several American pilots report that they frequently reach 8g. in pull-outs without suffering any adverse effect. It is therefore of interest to consider briefly what evidence there is from other walks of life of the accelerations which human beings can experience without injury.

At the Old Aquarium in Westminster, some 30-40 years ago, diving took place from a height of 100 feet into six feet of water. Last year at Berlin dives were made from 120 feet into a canvas tank of water six feet in depth. Both divers lost their lives (the first after many years) by striking the side of the tank. Even allowing for air resistance their deceleration must have exceeded 12g.

The man who fell at the Hotel Cecil a height of 50 feet was undoubtedly helped by the sliding of the ballast, but if he was steadily retarded for about four feet, he would only experience an acceleration of 12g. It is in keeping with many cases of persons who have fallen into dry dock with but small injury and with a fellow undergraduate roof-climbing who came down from 40 feet on to

a gravel path and got off with a broken ankle and wrist. Much of the undergraduate's body must have been at one time under an acceleration between 12 and 14g. Possibly the pilot who was unhurt after crashing into the roof of an empty house at Purley a few years ago experienced at least this acceleration.

Turning to every-day practice, recruits for the London Fire Brigade can be seen any Wednesday afternoon at Southwark jumping about 20 feet into a ground sheet held by men on the ground. Beginners get no shock absorption from their knees and do not seem upset by their 7g.

Turning to sport, there are many records of sprinters and jumpers breaking a bone during the take off. In fact, as regards both, torn muscles are not much more common than snapped bones. The medical authorities tell us that the bony structure of the human body is liable to break if it is subjected to more than 12 times its weight, and it may reasonably be deduced that the sprinter starting from his mark (or the jumper from the ground) by a sort of catapult spring, puts a local acceleration of more than 12g. on part of his foot. It may well exceed this as in normal running the foot has to accelerate from rest to at least the speed of the body (say 30 feet per second) during less than half a normal stride. Moreover, the body of the best sprinters reaches full speed in one small and two full strides (about 24 feet), which, although this is only a mean acceleration of 2g., must imply a very much greater initial acceleration. As another example, the Rugby three-quarter who comes down on the point of his shoulder to reduce his speed of 20 feet per second to zero in a distance of four to five inches (20g.) breaks his collar bone as he should; the remainder of his anatomy seems to suffer no injury whatever.

Let us turn now to minor discomforts. Many a person suffers from train and car sickness. An electric train accelerates only at a rate of $\frac{1}{4}$ to $\frac{1}{8}$g., and this is sufficient to make very sensitive passengers, with whom I have been travelling, quite sick, though usually only after several starts and stops. Such persons are abnormal. The pilot catapulted off the deck of a liner or warship is put under an acceleration of 3g. and suffers no discomfort provided his head be supported. In fact, the neck seems to be one of the weakest links in human physiology as anyone can calculate from the height of drop allowed for criminals; the same drop would also dislocate an arm or a leg—these are, of course, cases of relative acceleration of different parts of the body. Repeated accelerations of large amount are quite commonly experienced by children on the rod-suspended swings in the London parks. They can be seen to swing up to the horizontal, which means an acceleration of 3g. (if they went over the top it would be 5g., but I have never heard of this being done). We can, I think, say, however, that frequent large transient accelerations are, for many, a normal healthy exercise.

Very little is known about rate of acceleration, but the swing just quoted may be expected to reach the 3g. in less than half a second. Much higher values have been measured on recording accelerometers on aeroplanes. Rates of 5-10g. per second are common and up to 15g. have been recorded. It is not known whether pilots have experienced any discomfort when subject to such rapid change of acceleration, but medical authorities may be able to state how quickly a man can stiffen up various muscles to resist the rapidly changing forces on his body, but it is unlikely to be as quick as the ordinary reaction of hand and eye of 1/10th to 1/5th of a second.

The present position of our knowledge, in so far as I have been able to collect it, may be briefly stated as follows, but as many of the figures mentioned are tentative, criticism of them is invited.

(1) Only men of very good physique can stand a vertical acceleration of more than 5g. for many seconds.

(2) Most pilots can stand a very prolonged (several minutes) acceleration of 3g. vertically.

(3) It seems that a few persons have withstood a vertical transient acceleration of 12g. without injury or with only a broken bone, and many can experience 8g. without any loss of feeling other than a passing uncertainty.

(4) Most pilots feel no discomfort from a horizontal acceleration of 3g. if the head is supported, and they may be able to stand more.

(5) Intermittent horizontal accelerations, even when small, may give rise to minor discomforts.

One reason for suggesting that present flying practice may be well within physiological limits arises from a consideration of the more strenuous sport of dirt-track racing, where drivers have found it necessary to wear elastic belts to support their abdominal organs. Any figures on the rate of turning corners would be welcomed, as I have not heard that any acceleration experienced in an aeroplane has warranted the adoption of belts by aerobatic pilots.

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Membership

In the last two Council Reports the Council expressed the opinion that many in the Royal Air Force and the industry are not members of the Society who should be, and for the third time they wish to repeat this opinion.

In the last report attention was drawn to the fact that an Education and Examinations Committee of the Council was considering the revision of the Society's examinations and the exemptions from them. The reports of the Committee have now been passed by the Council and certain new rules which will be necessary following those reports will be submitted to the members at the Annual General Meeting. It was stated in the last Council Report that the tendency was for the examination standard to be raised, so that technical membership of the Society would be, practically speaking, an almost necessary qualification in the profession of aeronautics.

The new proposals appear in the February and March Monthly Notices of the Journal, and it will be seen from them that the examination standard has been raised and the list of exemptions very considerably curtailed. It is proposed that the new regulations should come into force on January 1st, 1933, and they will, undoubtedly, increase still further the rapidly rising prestige of the technical membership of the Society. It is the definite aim of the Council that every technical member shall be fully qualified in aeronautical science or engineering in the grade to which he is elected, and that time is now being reached.

As usual, the following table shows the membership for the past year and the previous one. The table reveals the fact that the membership of the main body has increased during the year, and the percentage rate of that increase remains substantially that of former years. The year 1931 has been such a difficult one that this result is all the more gratifying and in itself is symptomatic of the high standing of the Society. There has been, as was to be expected, a drop in the non-technical grade, and this is reflected, too, in the drop in the Branch membership, for which no technical qualifications are called. Part of the drop is accounted for by the Oxford Branch being under revision for service reasons. Against the drop there is the memberships of the Montreal and Ottawa Branches to be added, figures for which are not at present available.

The Cambridge University Aeronautical Society, which is affiliated to the Society, has a membership of about 300.

	No. of Members.		Hon. & Life Members.		Suspended.		Total.	
Fellows	110	(114)	20	(20)	—		130	(134)
Members	55	(38)	—		3	(5)	58	(43)
Assoc. Fellows ...	437	(394)	5	(5)	3	(9)	445	(408)
Assoc. Members ...	104	(88)	—		5	(12)	109	(100)
Associates	162	(142)	3	(2)	10	(16)	175	(160)
Companions	107	(143)	13	(15)	3	(6)	123	(164)
Founder Members ...	31	(33)	—		1	(1)	32	(34)
Students	271	(238)	—		10	(12)	281	(250)
Temp. Hon. Members	—		25	(23)	—		25	(23)
	1277	(1190)	66	(65)	35	(61)	1378	(1316)
Less Joint Members	28	(29)	—		—		28	(29)
	1249	(1161)	66	(65)	35	(61)	1350	(1287)
Branches:—								
Australia	35	(35)	—		—		35	(35)
Bristol	105	(135)	—		—		105	(135)
Coventry	214	(206)	—		—		214	(206)
Gloucester and Cheltenham	105	(137)	—		—		105	(137)
Leeds	50	(100)	—		—		50	(100)
Manchester ...	120	(120)	—		—		120	(120)
Yeovil	130	(350)	—		—		130	(350)
Oxford	—	(180)	—		—		—	(180)
	2008	(2424)	66	(65)	35	(61)	2109	(2550)

(Membership for 1930 shown in brackets.)

Endowment Fund

The table below shows the progress of the Endowment Fund:—

	£	s.	d.
December, 1926	575	0	0
December, 1927	597	2	0
December, 1928	1,047	18	0
December, 1929	1,077	6	0
December, 1930	1,265	10	0
December, 1931	1,935	10	1

The most remarkable fact about the above figures is that the increase of the Fund during 1931 was greater than during any previous year since the founding of the Fund. This is a tribute to the personal efforts of the President, Mr. C. R. Fairey. When his appeal was launched in December, 1930, neither he nor the Council could foresee the severity of the financial slump, and it is all the more gratifying therefore that the Fund should have made a record increase at a time when it was not to be expected. There is little doubt that in the future the Fund will begin to approach the amount the Council originally had in contemplation.

The Council urge every member to bear constantly in mind the very real importance of the Fund to the future work and stability of the Society. An adequate Fund will, indeed, place the Society in an unassailable position in

aviation throughout the world, and will enable the Society to have its own building and lecture hall, and the Council to proceed with schemes for the direct benefit of the members—schemes at present held in abeyance.

Donations

The Council wish to record their thanks to the Air Ministry, the Society of British Aircraft Constructors and the Society of Motor Manufacturers and Traders for their generous contribution of £250 a year each to the funds of the Society. This is the seventh year in succession the grant has been made by the Air Ministry and the Society of British Aircraft Constructors and the fourth year by the Society of Motor Manufacturers and Traders. These grants have proved of immense assistance to the Society and have enabled the Council to arrange for lectures, publications and other activities which would not otherwise have been possible.

Library

For the eighth year in succession the Council have to thank Mr. J. E. Hodgson, the Honorary Librarian, for the time he has given to the Library, and for the able advice which he has regularly given with regard to the books and acquisition of historical material. The Council have also to thank him for acting as their representative at the Council meetings of the National Central Library for Students and the Association of Special Libraries and Information Bureaux.

During the year many slides, photographs and books were acquired or presented to the Library by members and firms, acknowledgments of which were made in the Annual Summary of the Society's Activities in the Journal for December, 1931. The Society's collection of aeronautical slides is one of the finest in existence and is being added to steadily. It is hoped during the coming year to prepare a printed index of these slides.

The Council urgently suggest to all members who have slides, or photographs, or other aeronautical items of interest which they find any difficulty in storing, to look upon the Society as a suitable repository, to adopt the attitude of letting the Society have them on permanent loan. There they will be readily available for the member when he wishes to use them, and he will be rendering invaluable service by making them available to other members. This appeal particularly applies to slides and photographs, the requests for which have increased greatly during the past twelve months.

The Technical Index which was begun a few years ago has become increasingly useful each year, and is now a most valuable aid to members, who are constantly consulting it. The object of the Council, to induce anyone who wishes to obtain any information about aviation, to apply in the first place to the Society, is rapidly being achieved.

The experiment of opening the Library on Saturday afternoons has proved a success. The Library is closed alternate Wednesday afternoons for the meeting of the Council of the Society of British Aircraft Constructors, who have paid all the expenses of keeping the Library open on Saturday afternoons, and have in addition made a generous grant of twenty-five guineas to the Society in addition to their grant of £250.

The increasing demand for room for storing historical papers, documents, photographs and slides is making the problem of reorganising the Library one of some urgency.

Lecture Programme

A full list of lectures delivered before the Society, and the principal lectures delivered before the Branches, was given in the Journal for December, 1931. In

addition, the following lectures have been delivered or arranged for during the remainder of the present session :—

LECTURES BEFORE THE MAIN SOCIETY.

January 14th.—Mr. E. Ower, F.R.Ae.S. "Interference."

January 28th.—Mr. A. E. Woodward Nutt, B.A., A.F.R.Ae.S., and Flight Lieut. A. F. Scroggs. "Some Factors Affecting Range, with Special Reference to Height."

February 4th.—Dr. R. Benkendorff. "The Organisation of Air Routes and Aerodromes for Night Flying."

February 11th.—Mr. I. J. Gerard, M.Sc., A.F.R.Ae.S. "Tests of Aircraft Components."

February 25th.—Mr. P. Salmon. "Catapults and the Catapulting of Aeroplanes."

March 1st.—Mr. C. B. Dicksee. "Some Problems Connected with High Speed Compression-Ignition Engine Development." (Joint meeting with I.A.E.)

April 7th.—Mr. H. J. Stieger, D.I.C., A.F.R.Ae.S. "Wing Construction."

April 14th.—Mr. W. L. Taylor. "Aero Engine Accessories."

April 21st.—Mr. Nigel Norman, B.A., A.F.R.Ae.S. "Air Port Development."

May 5th.—Group Captain J. E. A. Baldwin, D.S.O., O.B.E. "The Training of Pilots and Instructors."

LECTURES BEFORE THE BRANCHES.

January 7th.—Yeovil Branch. Captain J. Laurence Pritchard. "Ten Years' Progress(?) in Aeronautics."

January 8th.—Hull and Leeds Branch. Major R. H. S. Mealing, A.R.Ae.S.I. "The Progress and Prospects of Civil Aviation."

January 14th.—Gloucester and Cheltenham Branch. Mr. I. J. Gerard, A.F.R.Ae.S. "Mechanical Testing."

January 14th.—Yeovil Branch. Mr. Tresilian, of Rolls Royce, on "Rolls Royce Schneider Engines."

January 19th.—Bristol Branch. Mr. F. Handley Page, C.B.E., F.R.Ae.S. "Some View Points in the Design of Modern Commercial Aircraft."

January 21st.—Gloucester and Cheltenham Branch. Captain C. D. Barnard. "Civil Aviation."

January 21st.—Yeovil Branch. Mr. H. J. Penrose, A.F.R.Ae.S. "A Visit to South America."

January 28th.—Yeovil Branch. Senor J. de la Cierva. "The Autogiro."

February 4th.—Gloucester and Cheltenham Branch. Squadron Leader W. R. D. Acland, D.F.C., A.F.C. "Deck Landing."

February 4th.—Yeovil Branch. Mr. Hodgson, A.I.D. "Engine Maintenance."

February 11th.—Gloucester and Cheltenham Branch. A Representative of Marconi Co.

February 11th.—Yeovil Branch. Mr. W. Widgery. "What Model Tests Teach Us."

February 12th.—Hull and Leeds Branch. Squadron Leader H. W. McKenna, D.C.M. "The Work of the Armament and Aeroplane Experimental Establishment at Martlesham Heath."

February 18th.—Gloucester and Cheltenham Branch. Mr. L. Martin. "Workshop Practice."

February 18th.—Yeovil Branch. Major C. J. Stewart, O.B.E., F.R.Ae.S. "Further Developments in Aircraft Instruments."

February 25th.—Yeovil Branch. Flight Lieut. E. A. Healy. "The Wapiti in England."

March 3rd.—Yeovil Branch. Mr. R. A. Denne, of Blakeborough and Sons, Ltd.

March 10th.—Yeovil Branch. Squadron Leader H. W. McKenna, D.C.M. "The Work of the Armament and Aeroplane Experimental Establishment at Martlesham Heath."

Wilbur Wright Memorial Lecture

The Wilbur Wright Memorial Lecture for 1931 was delivered before a distinguished audience on Wednesday, September 16th, 1931, by Mr. Glenn L. Martin, F.R.Ae.S., in the Aeronautical Section of the Science Museum, South Kensington, S.W.7. The subject of the lecture was "The Development of Aircraft Manufacture," and was printed in the Journal for October, 1931.

The Annual Council Dinner was held immediately preceding the Wilbur Wright Memorial Lecture, and a full list of those present was printed in the October, 1931, Journal.

Students' Section

The Students' Section during 1931 again continued to show a very satisfactory increase both in activity and membership. Many of the students are now being recruited from the Royal Air Force, and the Council again wish to thank all those officers who have taken a long view of the future careers of the men under them and encouraged them to become students and ultimately to prepare for the Society's examinations or those Royal Air Force examinations which exempt from those of the Society.

The Council wish to impress upon all students the importance of taking every opportunity for increasing their knowledge with the object of becoming technical members of the Society and so increasing their prospects. Technical membership of the Society is of definite value when applying for an appointment.

In November Mr. Mullett was appointed Secretary of the Students' Section and a new Committee was appointed. New rules for the Section were agreed upon at the Annual Meeting of the Students' Section. These rules are published in the March Monthly Notices.

In addition to the lectures announced in the December, 1931, Journal, the following have been given or arranged for before the Students' Section:—

February 2nd.—Mr. S. G. Hooker (Vice-Chairman). "Aerodynamics of Streamlining."

February 29th.—Mr. D. Hay Surgeoner. "Stressing."

March 8th.—Mr. S. D. Davies. "Performance."

March 17th.—Mr. W. F. Dewsett. "The Design of Aeroplane Control-Surfaces and Control-Systems."

April 19th.—Mr. G. W. Mullett (Secretary of Students' Section). "Torsion of Cylindrical Bars of Non-Circular Cross Section."

April 26th.—Mr. A. D. Hodgson. "Radio Communication in Aviation." Joint Lecture with London Students' Section of the Institution of Electrical Engineers, to be given at Savoy Place, Victoria Embankment, S.W.1.

Public Schools' Lectures

During the year the Public Schools were approached with the suggestion that members of the Society should deliver lectures before them. The response to the invitation showed that there was a very strong demand for aviation lectures and the Council arranged for a number of special slides to be prepared, with full notes on them, so that prospective lecturers would have the minimum amount of work to do in preparing the lecture.

In the December Journal a list of 22 schools was given before which lectures were read and below is a further list of schools for which lectures have been arranged this year. In addition to the schools mentioned, a number of other lectures to outside associations have been delivered. The attendance at the lectures already delivered has been over 5,000, and during this first year of the lectures the number of boys who will have heard the lectures will be between 12,000 and 15,000.

Many members of the Society at once signified their willingness to spare the time to deliver a lecture before a school, and some members have delivered a

number of these lectures. The Council wish to record their thanks to all those who have helped in this way in a work which they consider of primary importance. This first year has been in the nature of an experiment, but it is hoped next year to extend these lectures to some of the chief secondary schools and educational establishments. At many of the Public Schools the Air Ministry have a liaison officer and have signified their desire to co-operate with the Society in the delivery of future lectures. The Council would be glad to hear from any member who would be willing to lecture before a school in his neighbourhood. They feel it is of great importance that the opportunity of rousing interest in the air among those who are bound to have a great influence during the next few years should be seized upon.

In addition to those in the December Journal the following have been arranged:—

January 13th.—Watling Association at Barnfield School, Edgware. Captain J. Laurence Pritchard, Hon.F.R.Ae.S.

January 18th.—St. Olave's School. Mr. W. O. Manning, F.R.Ae.S.

January 22nd.—King's College School, Wimbledon. Captain J. Laurence Pritchard, Hon.F.R.Ae.S.

January 22nd.—Hull Grammar School. Mr. H. V. Whiting, A.R.Ae.S.I.

January 23rd.—Elstree School. Cmdr. L. D. Mackintosh, D.S.C., A.F.R.Ae.S., R.N.

January 25th.—Nottingham High School. Mr. W. P. Savage, A.F.R.Ae.S.

February 4th.—Worcester Royal Grammar School. Mr. F. Radcliffe, B.Sc., A.R.Ae.S.I.

February 4th.—Ryde Grammar School. Mr. T. A. S. Lloyd, Companion R.Ae.S.I.

February 6th.—Stowe School. Colonel the Master of Sempill, A.F.C., F.R.Ae.S.

February 8th.—Framlingham College. Mr. S. Scott-Hall, M.Sc., D.I.C., A.F.R.Ae.S.

February 8th.—Boys' School, Hillingdon. Mr. J. T. Morton, A.F.R.Ae.S.

February 8th.—King Edward's School, Southampton. W.-Cmdr. T. R. Cave-Browne-Cave, C.B.E., F.R.Ae.S.

February 11th.—King's College Engineering Society. Mr. C. E. Hoddle, Stud.R.Ae.S.I.

February 11th.—Alderman Newton's School, Leicester. Flight Lieut. C. W. Hewitt, A.R.Ae.S.I.

February 12th.—Wyggeston School, Leicester. Flt. Lieut. C. W. Hewitt.

February 12th.—College of Technology, Leicester. Flt. Lieut. C. W. Hewitt.

February 13th.—Working Men's College, Crowndale Road, N.W. Colonel the Master of Sempill, A.F.C., F.R.Ae.S.

February 15th.—Ipswich Guild. Mr. S. Scott-Hall, A.F.R.Ae.S.

February 17th.—Cranbrook School. Mr. J. E. Hodgson.

February 17th.—Bradfield College. Mr. H. L. Stevens, A.F.R.Ae.S.

February 19th.—Cranleigh School. Captain J. Laurence Pritchard, Hon.F.R.Ae.S.

February 19th.—Rutherford College. Mr. John Bell, A.R.Ae.S.I.

February 20th.—Royal Masonic School, Bushey. Flt. Lieut. J. B. H. Rogers.

February 23rd.—Epsom College. Captain J. Laurence Pritchard, Hon.F.R.Ae.S.

February 23rd.—Bruton School. Mr. H. J. Penrose, A.F.R.Ae.S.

February 23rd.—Wallasey Grammar School. Lieut.-Col. J. T. C. Moore-Brabazon, M.C., M.P., F.R.Ae.S.

February 27th.—Eastbourne College. Mr. S. Scott-Hall, A.F.R.Ae.S.

February 29th.—Royal Grammar School, High Wycombe. Major D. H. Kennedy, O.B.E., F.R.Ae.S.

March 2nd.—Brentwood School. Flight Lieut. R. E. H. Allen, A.M.I.A.E., M.I.Ae.E.
March 3rd.—Durham School. Dr. E. G. Richardson, B.A., D.Sc., Ph.D.
March 5th.—Reading School. Captain J. Laurence Pritchard, Hon.F.R.Ae.S.
March 9th.—Sherborne School. Mr. R. Blackburn, O.B.E., M.I.Mech.E., F.R.Ae.S., M.I.Ae.E.
March 12th.—Dean Close School, Cheltenham. Flight Lieut. R. E. H. Allen, M.I.Ae.E.
March 12th.—Highgate School. Mr. R. McKinnon Wood, O.B.E., F.R.Ae.S.
March 17th.—Royal Grammar School, Newcastle-upon-Tyne. Mr. John Bell, A.R.Ae.S.I.
March 18th.—Balshaw's Grammar School. Captain J. Laurence Pritchard, Hon.F.R.Ae.S.
March 26th.—Malvern College. Mr. H. P. Folland, M.B.E., F.R.Ae.S., M.I.Ae.E.

Branches

The year 1931 has been a difficult one for the Branches. The general financial situation and uncertainty has resulted in a general falling off of membership, but the activities of the Branches have not lessened. The Council feel, indeed, that the Chairmen, Committees and Secretaries of the various Branches have done work of the utmost value during the year in arranging lectures and keeping up an interest in aviation at a period when great difficulties have had to be encountered and overcome. The list of lectures read before the Branches is an imposing one and is in itself an eloquent testimony of the energy and enthusiasm of all those connected with the Branches. The Council urge upon everyone to support their Branches to the fullest possible extent, especially during periods of stress.

The newly-formed Branches at Ottawa and Montreal are a source of great gratification to the Council. The papers read before these Branches are printed in a special supplement of the Engineering Journal of Canada, and circulated with the Journal to all members. From opinions which have been received these papers have proved of very great value and constitute a strong link between Canadian and British Aviation. The first of the Dominion Branches to be formed was in Australia, and this Branch, despite the great difficulties of organisation is flourishing strongly under the able Secretaryship of Mr. J. V. Connolly. The following is a list of Branches and their addresses:—

Australia.—Hon. Secretary, J. V. Connolly, A.R.Ae.S.I., Science House, Gloucester and Essex Streets, Sydney, Australia.
Bristol.—Hon. Secretary, C. W. Tinson, F.R.Ae.S., M.I.Ae.E., Beaufort House, Southmead Road, Filton, Bristol.
Coventry.—Hon. Secretary, F. Meadows, A.F.R.Ae.S., "Llangstone," Jobs Lane, Coventry.
Gloucester & Cheltenham.—Hon. Secretary, L. W. Nethercott, A.R.Ae.S.I., "Bearswood," Glencairn Park Road, Cheltenham.
Hull & Leeds.—Hon. Secretary, Mr. G. B. Fenton, A.F.R.Ae.S., "Fairview," Brough, E. Yorks.
Manchester.—Hon. Secretary, Mr. T. Hampson, 57, Westbourne Road, Monton, Eccles, Manchester.
Yeovil.—Hon. Secretary, Mr. V. S. Gaunt, A.M.I.Ae.E., Westland Aircraft Works, Yeovil.
Ottawa Aeronautical Section.—Hon. Secretary, Squad. Ldr. A. Ferrier, A.F.R.Ae.S., Dept. of National Defence, Slater Street, Ottawa.
Montreal Aeronautical Section.—Hon. Secretary, 2050, Mansfield Street, Montreal, Canada.
Cambridge University Aeronautical Society (Affiliated).—Hon. Secretary, Wight Boycott, Scroope House, Cambridge.

AERIAL SCIENCE, LIMITED

Balance Sheet,

	£ s. d.	£ s. d.
Share Capital—		
Authorised—		
20 Shares of 1/- each and 999 Shares of £1 each	1000 0 0	
Issued—		
19 Shares of 1/- each, fully paid		0 19 0
Sundry Creditors		637 18 0
Amount owing to Endowment Fund – as per contra		163 3 7
Subscriptions Received in Advance		153 8 6
Carnegie U.K. Trust Grant for Purchase of Books – unexpended balance		34 11 5
Endowment Fund—		
Balance at 31st December, 1930	1265 10 1	
Add – Donations received during year	520 14 0	
Entrance Fees received during year	149 6 0	
		1935 10 1
Surplus –		
Reserve Fund—		
Balance as at 31st December, 1930	3553 0 9	
Income and Expenditure Account—		
Balance as at 31st December, 1930 ... ... 3194 16 0		
Add – Surplus of Income over Expenditure for the year to date 1612 9 7		
	4807 5 7	
		8360 6 4
		£11285 16 11

We report to the Members that we have examined the Books of the Society, and have obtained is properly drawn up so as to exhibit a true and correct view of the state of the Society's affairs us and as shown by the Books of the Society.

3, Frederick's Place, Old Jewry, London, E.C.2.
16th February, 1932.

Income and Expenditure Account

Dr.	£ s. d.
To Office Rent, Heating, Lighting and Insurance	549 7 0
,, Salaries	1034 5 4
,, Printing and Stationery	344 9 0
,, Postages, &c....	165 9 2
,, Office Expenses	184 12 7
,, Meetings	201 5 5
,, Journals, and Pamphlets (Less Sales)	841 16 3
,, Library Expenses	9 2 10
,, Audit Fee	29 8 0
,, Prizes and Donations	27 9 0
,, Dinners and Receptions	25 7 7
,, Subscriptions Written off	116 11 3
,, School Lectures	29 0
,, Surplus of Income over Expenditure for Year, carried to Balance Sheet	1612 9 7
	£5170 13 9

(The Royal Aeronautical Society).

31st December, 1931.

	£	s.	d.	£	s.	d.
Office Furniture, Printed Books, Bindings, Old Prints, etc., at cost, as at 31st December, 1930				450	5	11
Stock of JOURNALS *and other Publications*				763	3	7
Stock of Stationery				13	0	0
Sundry Debtors, including Subscriptions owing				202	15	9
Investments at Cost—						
£5552 3s. 0d. 5% War Stock, 1929/47	5565	4	9			
£1648 3s. 9d. 4½ % India Stock, 1958/68	1500	0	0			
(Market value at 31st December, 1931, £6450 16s. 7d.)				7065	4	9
Endowment Fund—						
£2043 19s. 8d. 3½% Conversion Stock	1584	18	3			
(Market value at 31st December, 1931, £1507 6s. 7d.)						
Cash at Bank	187	8	3			
Amount owing by General Funds, as per contra	163	3	7			
				1935	10	
Cash at Bank and in Hand—						
At Bank	851	13	9			
In Hand	4	3	1			
				855	16	10
				£11285	16	11

all the information and explanations we have required. We are of opinion that such Balance Sheet as at 31st December, 1931, according to the best of our information and the explanations given to

(Signed) PRICE, WATERHOUSE & CO.

for the Year Ending 31st December, 1931.

Cr.	£	s.	d.	£	s.	d.
By Annual Subscriptions				2992	9	10
,, Interest on Investments (*Less* Tax)	333	4	7			
,, ,, ,, Deposit	21	2	7			
,, ,, ,, Endowment Fund Investments (*Less Tax*)	48	10	0			
				402	17	2
,, Donations				1772	2	6
,, Sale of Badges				3	4	3
				£5170	13	9

AERONAUTICAL

Balance Sheet,

	£ s. d.	£ s. d.	£ s. d.
Share Capital —			
Authorised —			
40 Shares of 1/- each		2 0 0	
Issued —			
21 Shares of 1/- each		1 1 0	
Less — Calls in arrear		1 1 0	
Pilcher Memorial Fund—			
Capital Account —			
As at 31st December, 1930.		99 14 0	
Income Account —			
Balance as at 31st December, 1930	25 8 8		
Add Surplus of Income over Expenditure for year to date	15 4	26 4 0	
			125 18 0
Usborne Memorial Fund—			
Capital Account —			
As at 31st December, 1930		109 2 5	
Income Account —			
Balance as at 31st December, 1930	13 5 5		
Add Surplus of Income over Expenditure for year to date	5 13 0	18 18 5	
			128 0 10
Herbert Akroyd Stuart Fund—			
Capital Account —			
As at 31st December, 1930		688 19 0	
Income Account —			
Balance as at 31st December, 1930	34 5 0		
Add Surplus of Income over Expenditure for year to date	34 3 0	68 8 0	
			757 7 0
R.38 Memorial Fund—			
Capital Account —			
As at 31st December, 1930		978 3 10	
Income Account			
Balance as at 31st December, 1930	185 19 10		
Add Surplus of Income over Expenditure for year to date	26 3 6	212 3 4	
			1190 7 2
Edward Busk Memorial Lecture Fund—			
Capital Account —			
As at 31st December, 1930		449 6 1	
Income Account —			
Balance as at 31st December, 1930	69 14 9		
Add Surplus of Income over Expenditure for year to date	16 0	70 10 9	
			519 16 10
Wilbur Wright Memorial Fund—			
Capital Account —			
As at 31st December, 1930		1298 9 9	
Income Account —			
Balance as at 31st December, 1930	81 18 11		
Add Surplus of Income over Expenditure for year to date	3 14 0	85 12 11	
			1384 2 8
Simms Gold Medal Fund—			
Capital Account —			
As at 31st December, 1930		250 0 0	
Less — Income Account Deficiency as at 31st December, 1930	1 14 6		
Add Excess of Expenditure over Income for year to date	7 0 8	8 15 2	
			241 4 10
			£4346 17 4

We report to the Members of Aeronautical Trusts, Ltd., that we have examined the above
explanations we have required. We are of opinion that the Balance Sheet is properly drawn up
December, 1931, according to the best of our information and the explanations given to us and as

3, Frederick's Place, Old Jewry, London, E.C.2.
16th February, 1932.

TRUSTS, LTD.

31st December, 1931.

	£ s. d.	£ s. d.
Pilcher Memorial Fund—		
£115 6s. 10d. 5 % War Stock, 1929/47, at cost	116 5 0	
Cash at Bank	9 13 0	
		125 18 0
Usborne Memorial Fund—		
£113 5 % War Stock, 1929/47, at cost	114 11 1	
Cash at Bank	13 9 9	
		128 0 10
Herbert Akroyd Stuart Fund—		
£683 1s. 0d. 5 % War Stock, 1929/47, at cost	698 19 0	
Cash at Bank	58 8 0	
		757 7 0
R.38 Memorial Fund—		
£1048 11s. 2d. 5 % War Stock, 1929/47, at cost	1098 18 10	
Cash at Bank	91 8 4	
		1190 7
Edward Busk Memorial Fund—		
£284 4s. 2d. 5 % War Stock, 1929/47, at cost	284 4 2	
£245 Metropolitan Railway 4 % Debentures at cost	200 1 11	
	484 6 1	
Cash at Bank	35 10 9	
		519 16 10
Wilbur Wright Memorial Fund—		
£1047 6s. 7d. 3½ % Conversion Stock, at cost	800 0 0	
£550 Canadian 4 % Stock, at cost	531 10 9	
	1331 10 9	
Cash at Bank	85 12 11	
	1417 3 8	
Less—Amount owing to Aerial Science, Ltd.	33 1 0	
		1384 2 8
Simms Gold Medal Fund—		
£287 16s. 1d. India 4½ % Stock, 1958/68, at cost	250 0 0	
Cash at Bank	7 19 10	
	257 19 10	
Less—Amount owing to Aerial Science, Ltd.	16 15 0	
		241 4 10
		£4346 17 4

Balance Sheet with the books of the Company and have obtained all the information and so as to exhibit a true and correct view of the state of the Company's affairs as at 31st shown by the books of the Company.

PRICE, WATERHOUSE & CO.

AERONAUTICAL

INCOME & EXPENDITURE ACCOUNTS

Pilcher

RECEIPTS.

	£	s.	d.
To 1931 Award	5	0	0
,, Surplus of Income over Expenditure for year carried to Balance Sheet	0	15	4
	£5	15	4

Usborne

,, Surplus of Income over Expenditure for year carried to Balance Sheet	5	13	0
	£5	13	0

Herbert Akroyd

,, Surplus of Income over Expenditure for year carried to Balance Sheet	34	3	0
	£34	3	0

R.38

To 1931 Award	26	5	0
,, Surplus of Income over Expenditure for year carried to Balance Sheet	26	3	6
	£52	8	6

Edward Busk

To 1931 Award	21	0	0
,, Surplus of Income over Expenditure for year carried to Balance Sheet	0	16	0
	£21	16	0

Wilbur Wright

To 1931 Award	50	0	0
,, Surplus of Income over Expenditure for year carried to Balance Sheet	3	14	0
	£53	14	0

Simms Gold

To 1931 Award	16	15	0
	£16	15	0

TRUSTS, LTD.

FOR THE YEAR ENDED 31ST DECEMBER, 1931.

Memorial Fund

PAYMENTS.

	£ s. d.
By Interest on Investments (gross)	5 15 4
	£5 15 4

Memorial Fund

By Interest on Investments (gross)	5 13 0
	£5 13 0

Stuart Fund

By Interest on Investments (gross)	34 3 0
	£34 3 0

Memorial Fund

By Interest on Investments (gross)	52 8 6
	£52 8 6

Memorial Lecture Fund

By Interest on Investments (*less* Tax)	21 16 0
	£21 16 0

Memorial Fund

By Interest on Investments (*less* Tax)	53 14 0
	£53 14 0

Medal Fund

By Interest on Investments (*less* Tax)	9 14 4
,, Balance being Excess of Expenditure over Income for year carried to Balance Sheet	7 0 8
	£16 15 0

President

At the meeting of Council held on May 19th, 1931, Mr. C. R. Fairey, M.B.E., F.R.Ae.S., was unanimously elected President for a second year of office, October, 1931-September, 1932.

Mr. Fairey's term as President has coincided with one of the most severe financial depressions ever experienced. Mr. Fairey, however, has proved a tower of strength to the Society financially and otherwise. Thanks to his own personal efforts the Endowment Fund was increased during his first year of office by over £600, the greatest increase in any one year since the Fund was started. There is little doubt that when the financial situation changes the seeds sown in 1930-32 by the President will bring substantial benefit to the Society. In many other ways, during his period of office, Mr. Fairey has personally paid considerable sums which the Society would otherwise have to meet, notably the heavy deficit for the Wilbur Wright Memorial Lecture and Conversazione and the entertainment of lecturers from abroad. The Council wish to express their grateful thanks and deep appreciation of the time, energy and financial assistance which the President has given to the Society, all of which are reflected in the increasing prestige, membership and sound financial position of the Society at the present time.

Journal

The growth and influence of the JOURNAL have continued during 1931 and the revenue from its outside sales reached a figure of £1,370 during a period when it was expected that its sales would drop heavily. The circulation of the JOURNAL for 1931 shows no drop over that for 1930, a remarkable tribute to its value when the circulations of most technical journals have shown a decline. The destination of the great majority of JOURNALS sold to non-members can be accurately ascertained, and an analysis shows that the JOURNAL circulates in every country where aircraft are used or constructed.

Finance

The Balance Sheet and Income and Expenditure Account of Aerial Science, Limited, are published in this issue of the JOURNAL. The form in which the accounts are drawn up shows an excess of income over expenditure for the year under review of £1,612 9s. 7d. The Council wish to point out that the excess is entirely due to generous donations which have been received, amounting in all to £1,772 2s. 6d. Deducting the donations, which are in no sense permanent sources of income, but are entirely dependent upon the good will of the donors, there is an actual loss on the year of £159 12s. 11d. This compares with an actual loss of £186 14s. 2d. in 1930, £862 in 1929 and £600 in 1928. In one sense, therefore, definite progress is being made and the Society is to be congratulated that the loss in the recent difficult financial year is actually the lowest of recent years.

An analysis of the Balance Sheet compared with that of 1930 shows an increase in rent of £120 a year, a decrease of £60 in the salaries, printing and stationery, postages and office expenses and an increase in the cost of the JOURNAL and other publications of £230. The annual subscriptions have increased—a very satisfactory sign—and the interest on the Society's investments is now £400 a year. In 1926 that interest was less than a tenth of that for 1931.

The Society is undoubtedly in a very much sounder financial position than it was five years ago, but it is not yet self-supporting, and the Council urge every member to keep that fact in his mind and to use his influence to increase the membership of the Society and to add to the Endowment Fund in order that the Society shall be in a position which makes it independent of the fluctuations of world finance and trade.

Honorary Solicitor

Mr. Lawrence A. Wingfield, M.C., D.F.C., A.R.Ae.S.I., has continued to act as Honorary Solicitor to the Society and the Council wish to place on record the valuable services he has rendered. The formation of Aeronautical Trusts, Limited, has been completed and Mr. Wingfield has prepared new Articles of Association for Aerial Science, Limited, and simplified considerably the work in connection with both companies. He has advised the Council on a number of important legal questions and has served on the Education and Examinations Committee, which has been considering new regulations for technical membership of the Society.

Honorary Treasurer

The Council have had the advantage of the services for the fifth year in succession of Major D. H. Kennedy, O.B.E., F.R.Ae.S., the Honorary Treasurer and Chairman of the Finance Committee. Upon Major Kennedy and the Committee during 1931 has fallen the onerous task of conserving the finances of the Society without lessening its activities. Major Kennedy has been fertile in his suggestions for increasing the income of the Society and the Council wish to place on record the debt which they and all members owe to Major Kennedy for his untiring energy on behalf of the Society.

Honorary Accountant

Mr. Norman Smith, the Honorary Accountant, has, during 1931, finished his fourth year of office. During that year Mr. Smith has paid special attention to the Income Tax problems, and has been in constant communication with the Commissioners of Inland Revenue, and there is every hope that his labours on behalf of the Society will prove successful. The Council wish to record their grateful thanks for the work and excellent advice which Mr. Smith has so constantly and freely given to the Society, greatly to its advantage.

Staff

The Staff of the Royal Aeronautical Society is among the smallest staffs of any corresponding Society, and the salary list, as a percentage of the income of the Society, is very considerably below that of similar societies. It is worth recording that since 1924 the salaries, as a percentage of income, have steadily dropped from 54.0 per cent. in that year, to 20.2 per cent. in the year ending December 1931. During the past six years the office work of the Society has increased very rapidly as new schemes have been initiated. The Council initiate such schemes, but it is upon the staff that the real work falls, and upon them that the final efficiency of the administration of the Society depends. The Council wish to record how excellently the work of the Society has been carried out by the Staff, Miss Jarvis, Miss Todd, and Miss Voyce, and the Secretary, Captain J. Laurence Pritchard.

CORRESPONDENCE

The Secretary, Royal Aeronautical Society, 7, Albemarle Street, London, W.1, England.

Department of National Defence
(Office of the Chief Aeronautical Engineer),
Ottawa, Canada,
January 23rd, 1932.

Dear Sir,—

1. I have read with considerable interest the excellent paper by Mr. Sutton on The Protection of Metal Parts of Aircraft against Corrosion. This paper covers a number of important problems which arise in the maintenance of aircraft.

2. It is considered, however, that sufficient prominence has perhaps not been given to corrosion, which occurs in the presence of dissolved oxygen. In his publication, "The Corrosion of Metals," Evans refers to this very important phase of corrosion, and his key experiment described on page 80 is of particular interest. In this experiment Evans shows that when two plates of the same material are immersed in a liquid and arranged so that one plate is aerated an electric current is set up.

3. On page 93 of the same book Evans states in part "corrosion is likely to persist most readily in places to which oxygen has less access, provided that these inaccessible places are not far removed from places to which oxygen can penetrate freely. An important feature of the type of corrosion set up by differential aeration is that the anodic cranny is often small compared to the cathodic area, and thus the whole effect is concentrated on a small area."

4. This type of corrosion seems to have particular bearing upon a trouble which we have experienced for a long period, that is, the corrosion of the bottom rear longerons of tubular fuselages. As originally constructed these fuselages have the fabric in contact with the longeron, with the result that not only does this position collect moisture, but also the metal in this position is deprived of air.

5. The life of a fuselage of this type has been found to be improved by welding small pieces of plate on edge to the longerons and placing a strip for holding the fabric outside these small distance pieces. The fabric strip can be made of wood or duralumin, and deterioration of this strip is not important, whereas deterioration of the longeron is prevented, because it is given free access to the air throughout its whole length.

Yours very truly,
E. W. STEDMAN,
Group Captain,
Chief Aeronautical Engineer.

REVIEWS

Who's Who in British Aviation

(Airways Publications, Ltd.).

The Director of Civil Aviation in a foreword to *Who's Who in British Aviation*, says it "has already proved its value and can now be regarded as a standard work of reference."

There is no doubt as to its value, a value which will increase each year until the Aviation Who's Who becomes as indispensable as that greater Who's Who. One misses well-known names in aviation, but one's knowledge of the difficulties of compilation makes it certain that most of the missing are so because they were neglected or do not wish to send in particulars to the publishers. And this attitude of mind is, we believe, a mistake. There are names which definitely ought to be there, to take those in A for example: Captain Peter Acland, Patrick T. Alexander, R. E. H. Allen, H. J. Andrews, and S. T. G. Andrews.

Who's Who in British Aviation contains a number of useful sections including Aircraft Operating Companies, Aircraft Constructors and Engine Constructors, Manufacturers, Aircraft Accessories and Components, and a list of Flying Clubs among others.

Jane's All the World's Aircraft, 1931

(Sampson Low. 42/- net.)

The 1931 edition of this book differs little from its predecessors except, of course, in the inclusion of new matter and the exclusion of the obsolete; the only innovation being a series of technical notes on the trend of design by the Editor, Mr. C. G. Grey. These notes add to the interest of the work, but the importance of the subject would justify a more detailed treatment.

It is a tribute to the buoyancy of the Aeronautical Industry all over the world that this issue of *Jane's* is slightly larger than the last, showing that, in spite of the industrial slump, the Industry is maintaining its enterprise. There is unquestionably a steady improvement in the design of both aircraft and engines, but it is, perhaps, only to be expected that the youngest of the great industries should show itself to be the most virile.

The collection of aeronautical data to be found in *Jane* is invaluable. Those who desire to purchase aircraft will find detailed and illustrated descriptions of every modern aeroplane set out conveniently for comparison and selection. Those who manufacture aircraft or engines will find descriptions of all machines manufactured by their competitors and can judge whether they have gained or lost places in the race for improvement, while for the student of the trend of design the various editions of the work form a repository of information which can be found nowhere else in so convenient a form. The book is one which it is superfluous to recommend; it is an absolute necessity to all interested in aeronautics.

The Modern Diesel

(Iliffe & Sons.)

This book is written for the purpose of explaining to the non-technical man the method of operation of the Diesel engine. It naturally does not go deeply into the subjects it deals with, but it explains the principles of Diesel operation

in simple and clear language and should undoubtedly help amateur owners of this type of engine to understand how they work.

The book is very well illustrated and contains descriptions and drawings of most of the current types of fuel pumps and cylinder heads. Illustrated descriptions are given of a large number of engines of road transport, marine and aeronautical types, with details of power output, weight and fuel consumption.

There seems to be an error in the curve given on page 9, where the engine with the larger M.E.P. is apparently credited with the lower horse-power at the same speed. There are also inconsistencies in some of the other curves, fuel consumption being sometimes given in pints per hour, and sometimes in pounds per hour; one curve is even expressed in metric units. These matters make comparison difficult and should be put right in future editions.

This type of book unquestionably fulfils a want as it falls into the hands of, and interests, those who would never consult an ordinary text book. Many of those who read it should be encouraged to study a more advanced work.

This book well fulfils the purpose for which it was written and can be thoroughly recommended.

Hydro und Aeromechanik

L. Prandtl and O. Tietjens. In two vols. (J. Springer, Berlin.)

The Aeronautical Department of the University at Göttingen has now attained world-wide fame under the able guidance of Prof. Prandtl. Dr. Tietjens, one of his former colleagues and students, has undertaken to write out his lecture notes in the form of a book, which has been edited by the lecturer himself. An extraordinary amount of useful matter has been included in these two small volumes, and mere statistical information has been reduced to a minimum.

The first book deals with classical aerostatics and aerodynamics, and the second with the mechanics of real fluids and aerodynamic research. The reader must remember, as Prof. Prandtl points out in a foreword, that the book is a course of lectures, and as such must not be expected to be complete on the bibliographical side. One or two practical examples to illustrate each point of the theory are brought forward, if further examples are required they must be sought in the literature or large reference books on the subject.

In the first book the practical applications of hydrostatic theory are naturally applied to balloons and airships. This part includes a very short chapter on surface tension. Then follow sections dealing with frictionless fluids, potential streaming and conformed transformation, and the effects produced when compressibility is introduced into the Bernouilli and continuity equations. A short section is devoted to the theory of the impulse or jet propeller, although no practical application of this principle is mentioned.

In the second volume we are introduced to the concept of viscosity and the law of dynamical similarity. The third section on flow in tubes goes a little outside the actual lecture course, giving us a little of the history of the discovery of a critical velocity, and a very full account of the classical investigation of Osborne Reynolds on this subject. A very important section on the boundary layer follows. This, of course, is pure Prandtl, and the reader may here obtain an *ex cathedra* review of the present position of this question. The resistance of spheres is next subject for consideration, including an as yet unpublished calculation of Prandtl's on the resistance of a body in relation to the impulse of the stream upon it. Next follows the aerofoil and the circulation theory, and certain matters connected with the lift of wings having finite length.

The final sections, which were not included in the original course of lectures, deal with methods of research and instruments. This is most interesting, and gives a rapid and up-to-date summary of the technique of modern aerodynamic laboratories. The beautiful photographs of flow given at the end round off a most interesting treatise.